Bus-Based Content Offloading for Vehicular Networks

Zhe Wang, Zhangdui Zhong, Minming Ni, Miao Hu, and Chih-Yung Chang

Abstract: **Vehicular ad hoc networks (VANETs) represent the promising technologies for comfort driving and infotainment applications which rely heavily on the content offloading. Due to the rapid change of network topology and intermittent connection, it is a big challenge to satisfy the content requests from multi-sedans at the same time. This paper proposes a bus-based content offloading (BBCO) algorithm which aims to maximize the volume of offloaded content from bus to sedans while the offloading opportunity fairness of each sedan is also taken into consideration. By predicting the number of buses which the sedan would encounter in its future path and estimating the transmission rate, the BBCO algorithm schedules the content offloading service for sedans slot by slot to maximize the offloaded content volume and guarantee the offloading opportunity fairness. The effectiveness of the proposed algorithm is evaluated by extensive simulations.**

Index Terms: **Bus-Based Content Offloading, content offloading, maximize, offloading opportunity fairness, vehicular ad hoc networks (VANETs).**

I. INTRODUCTION

WITH the development of wireless communication technologies, vehicular ad hoc networks (VANETs) have become one of the key components in the future intelligent transportation systems (ITS) [1]. Due to the growth in the size of cities, people spend more time driving on their daily commute. A recent report shows that, in Europe, the average time spent in driving is 274 hours a year per person, while it is up to 541 hours in America [2]. In order to facilitate more comfort driving and enjoyable journey, VANETs promise a wide range of valuable applications including travel assistance and vehicle infotainment, which also result in much higher content volume (e.g., picture, audio and video) to be offloaded to the drive-thru vehicles. The blooming is such, that mobile data traffic demand is expected to be continuously rising with a rate of more than 100% per year [3]. The vehicular network is being transformed into the service-oriented network which relies on both vehicle to infrastructure (V2I), and vehicle to vehicle (V2V) communications [4], [5]. Therefore the data source pool need to cope with the increase in data volumes and ensure transmission fairness to meet content requests of the subscribers in VANETs. However, there are some unique characteristics of VANETs, such as the rapid change of network topology and intermittent connection. So it is a very challenging task to satisfy all the content requests from vehicles in the network.

Many content offloading algorithms have been proposed , which can be classified into two classes: Road side unit (RSU)-based algorithm and parked vehicle-based algorithm. Nevertheless, due to large amount of investment and the unwilling participation of the drivers, the above algorithms may be difficult to conduct in reality. To address these issues, this paper proposes a new algorithm called *bus-based content offloading (BBCO)* algorithm which utilizes buses to constitute the backbone network to serve vehicles with content requests. Two types of vehicles, the sedans and the buses, are considered in BBCO algorithm. The BBCO algorithm aims to maximize the volume of offloaded data while it also takes into account the fairness of offloading opportunity. The BBCO algorithm is built upon the prediction that the number of buses which sedan would encounter in its future path and the estimation of the transmission rate that the sedan could offload data from the bus. A discrete-time model is introduced to analyze the duration of the bus driving on the highway. The contributions of this paper can be summarized as follows.

1) The BBCO algorithm estimates the time duration of sedans within the coverage area of the bus and formulates the profit matrix. Based on the above studies, the BBCO algorithm could offload larger data volume, as compared with the existing algorithms.
2) By predicting the number of buses which the sedan would encounter in its future path, the BBCO algorithm could derive the degree of urgency for each content request, which could help the BBCO algorithm to guarantee the offloading opportunity fairness.
3) To balance the relationship between the offloaded data volume maximization and offloading opportunity fairness, a *Selection Function* is proposed to select a sedan to offload data from the bus when many content requests are presented at the same time.

The rest of this paper is organized as follow. The related works are introduced in Section II. Section III proposes the considered network model and problem formulation. The details of the BBCO algorithm is presented in Section IV. Section V investigates the performance improvement of the proposed algorithm against the existing works. The conclusion of this paper is drawn in Section VI.

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II. RELATED WORKS

The surge of travel assistance and vehicle infotainment applications in VANET have motivated the extensive research efforts on the design of efficient vehicular content offloading algorithms. In this section, we summarize the two mainstream content offloading algorithms in VANETs: 1) The RSU-based content offloading algorithm [7]–[12], 2) the parked vehicle-based content offloading algorithm [13]–[16].

1) *RSU-based content offloading algorithm:* The RSU-based algorithm assumed that RSUs are deployed at the roadside, vehicles can offload data from them. Zhioua *et al.* [7] investigate on the optimization problem which is aiming to elect the maximum number of data flows. Wang *et al.* [8] develop an adaptive offloading strategy which is based on the encountering time prediction between vehicles and RSUs. Ota *et al.* [9] propose a cooperative offloading algorithm, which maximizes the amount of content packets offloaded from the RSUs while minimizing delivery delay of each user request. Lochert *et al.* [11] present a genetic algorithm which is able to identify good positions for RSUs in order to cope with the highly partitioned nature of the VANETs. However, the RSU can be accessible only when the vehicle is within its communication range. Furthermore, the cost of deploying RSUs seamlessly is difficult to accept. In this paper, the proposed algorithm utilizes buses to constitute the backbone network to serve vehicles with content requests, which could help the user prolong the link duration between source pool and the vehicle.
2) *Parked vehicle-based content offloading algorithm:* Motivated by the extensive parking in cities, a collection of papers have been devoted to analysis of parked vehicle-based content offloading algorithm. Liu *et al.* [13] develop a content offloading strategy to leverage roadside parking to distribute contents in urban VANETs. Malandrino *et al.* [14] investigate the possibility of exploiting parked vehicles to extend the RSU service coverage at a small cost in terms of battery utilization for the parked vehicles. By using parked vehicles as relay agents between moving vehicles and APs, [16] isolates the detrimental effects of slow connection times and poor throughput to the vehicle. However, the offloading algorithms based on parked vehicles may be difficult to conduct in reality, because some drivers are not willing to offer service for others and the wireless devices of their vehicles are usually shut down when their vehicles are parked. Another critical problem is that most existing algorithms arrange the content offloading schedule based on the connection sequence of vehicles. The high degree of the buses' openness could overcome the above issues. [17] proposes a data delivery in a realistic bus network, which is aiming to maximize the delivery probability by a given deadline. [18] presents a routing algorithm that achieves effective data delivery in a buses environment. In this paper, the proposed algorithm is aiming to maximize the volume of offloaded data while it also takes into account the fairness of offloading opportunity.

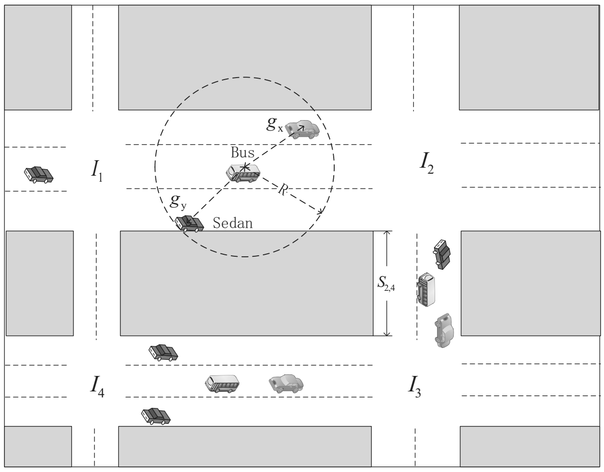

Fig. 1. System model of bus-based content offloading.

III. MODEL DESCRIPTION

A. System Model

In our analysis, the observed time duration is denoted as T. The considered vehicular networks can be represented by $VN = (G, B, S, E)$, which is shown as Fig. 1. The vehicles considered in VN are generally categorized into buses and sedans, which are generally denoted as b and g, respectively. The set of the buses and the sedans in VN can be denoted as B and G, respectively. The bus with various kinds of contents is regarded as a moving resource pool to provide content for nearby sedans. Let S denote the set of segments that we observed in the networks, $S = \{s_{x,y} | s_{x,y}$ is the segment from intersection I_x to intersection $I_y\}$. The segment has multiple lanes. Each vehicle is assumed to be equipped with a wireless device by which it can communicate with other vehicles within its communication range R. There is a link in E between a sedan $g_i \in G$ and a bus $b_j \in B$ when they are within the communication range of each other.

We consider a bus $b_p \in B$ driving along a pre-defined unidirectional road segment $s_{i,j} (s_{i,j} \in S)$ with length L by a constant speed $v(b_p)$ to provide contents to its nearby sedans. We here adopt a discrete-time model proposed in [19] to partition the duration of the tour into several time slots of the same length τ. Let T_L denote time duration of the tour, which can be determined by $T_L = [L/(v(b_p) \cdot \tau)]$. The paper index the T_L time slots by 1, $2, \cdots, t_L$, which is shown in Fig. 2. Let G_L $(G_L \subseteq G)$ denote the set of k sedans which could connect to bus b_p at the road segment $s_{i,j}$. Let $C_{g_x} = [x_s, x_e]$ represent the set of consecutive time slots that the sedan g_x $(g_x \in G_L)$ can connect to the bus, which x_s and x_e denote the starting time and the ending time. The C_{g_x} is determined by two factors: 1) the relative speed between g_x and b_p, 2) the distance from the lane which is occupied by g_x to the lane which b_p is driving on. The driving speed of $g_i \in G$ follows the Gaussian distribution, $v(g_i) \sim N(\mu, \sigma^2)$. We assume that there are two sedans g_x and g_y $(g_x, g_y \in G_L)$ which are in the communication range of b_p, $C_{g_x} = [x_s, x_e]$ and $C_{g_y} = [y_s, y_e]$. If $C_{g_x} \cap C_{g_y} \neq \varnothing$, g_x and g_y share some time slots that both of them can offload data from the bus. For the media access control, the standard CSMA/CA scheme is applied in the network. Therefore, the bus could only provide offloading service for one sedan, when many sedans submit content requests at the same time slot. The CSMA/CA is a MAC protocol that a node verifies the absence of other traffic before transmitting on a shared transmission medium at a time slot, which is used to determine whether this time slot is available for the sedan. While the proposed time slot allocation schedule is to arrange the available time slot for each sedan. We believe the hybrid scheme is more adaptive to the dynamic vehicular network scenario.

To describe a signal's power attenuation, a dual-slope piecewise-linear model [20] is applied here as

$$P_{\rm r}(d)=\begin{cases} P_{\rm r}(d_0)+10h_1\log_{10}(\frac{d}{d_0})+X_{\sigma_0}, & d\le d_b;\\ P_{\rm r}(d_0)+10h_1\log_{10}(\frac{d_b}{d_0})+10h_2\log_{10}(\frac{d_b}{d_b})+X_{\sigma_0}, & d>d_b, \end{cases} \quad (1)$$

where $P_{\rm r}(d_0)$ is the known signal strength at the reference distance d_0. h_1 and h_2 are the path loss exponents. d_b is the breakpoint distance which can be calculated as $d_b=\frac{4\omega_i\omega_j}{\lambda_w}$ with ω_i,ω_j denoting the antenna heights of vehicles i and j, respectively, and λ_w denoting the wavelength of the electromagnetic wave. X_{σ_0} is a zero-mean normally distributed random variable with the standard deviation σ_0. Moreover, the Nakagami fading model is also used to describe the channel's fading effect. Therefore, the power Z received from the bus with distance d away has the probability density function (PDF) as

$$f_Z(z)=\frac{1}{\Gamma(m)}\left(\frac{m}{\overline{P}_{\rm r}(d)}\right)^m z^{m-1}\exp\left(-\frac{mz}{\overline{P}_{\rm r}(d)}\right), \quad (2)$$

where $\Gamma(m)=\int_0^\infty e^{-t}t^{m-1}\,{\rm d}t$ is the Gamma function, and m is the fading parameter. For $m=1$, (2) reduces to Rayleigh distribution; and for $m=\frac{(K+1)^2}{2K+1}$, (2) becomes the Ricean fading with parameter K. Besides, $\overline{P}_{\rm r}(d)$ is the mean received signal power as shown in (1).

We refer to the analysis in [21] and obtain the cumulative density function (CDF) of the received power z,

$$\Pr\{z\le x\}=1-\frac{\Gamma(m,\frac{m}{\overline{P}_{\rm r}(d)}x)}{\Gamma(\mu_0)}, \quad (3)$$

where $\Gamma(m,\frac{m}{w}x)=\int_{\frac{m}{w}x}^{\infty}y^{y-1}\exp(-y){\rm d}y$.

With (3), the CDF of the signal to noise ratio (SNR) at the receiver is

$$\Pr\{\frac{z}{\delta}\le x\}=1-\frac{\Gamma(m,\frac{m}{\overline{P}_{\rm r}(d)}\delta x)}{\Gamma(\mu)}, \quad (4)$$

where δ denotes the thermal noise power at the receiver.

We assume that there are e discrete transmission rates denoted as $\Theta=\{q_1,q_2,\cdots,q_e\}$ with $q_1<q_2<\cdots<q_e$, and the transmission rates are adapted in the SNR-triggered manner as Table 1 [21]. Specifically, transmission rate q_j $(1\le j\le e)$ is associated with a predefined SNR threshold u_j. The transmission rate q_j is adopted if the current SNR is above u_j and smaller than u_{j+1}. As such, based on the headway distance, the transmission rate q_j is selected with probability

$$\Pr\{Q=q_j\}=\Pr\{u_j<\frac{z}{\delta}\le u_{j+1}\}\ \text{for}\ 1\le j\le e-1. \quad (5)$$

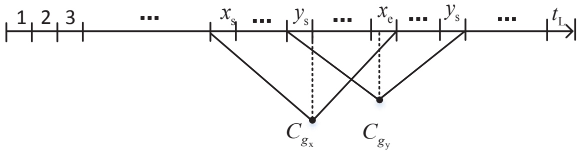

Fig. 2. An illustration of discrete-time model for the duration of a bus in the pre-defined highway.

Table 1. DSRC data rate and SNR threshold.

SNR threshold (dB)	5	6	8	11	15	20	25	N/A
Data rate (Mbps)	3	4.5	6	9	12	18	24	27

The data transmission rate between the sedan and the bus at time slot t could be derived as

$$r(t)=\sum_{1}^{e}q_j\cdot\Pr\{Q(t)=q_j\}\ \text{for}\ 1\le t\le T_{\rm L}. \quad (6)$$

B. Problem Definition

Here, we present the formulation of the investigated content offloading problem and outline the goal of this paper. This paper aims to investigate the problem that how each bus schedules its offloading services slot by slot when many sedans submit content request at the same time, and the goal of the proposed algorithm is to maximize the throughput under the premise of guaranteeing fairness. To measure the throughput, a *Throughput Index* of the sedan is proposed, which is denoted by $I_{\rm throughput}$. The *Throughput Index* represents the ratio of the total offloaded content volume to the requested volume. Let $D_{g_{\rm x}}$ and $a_{g_x,l}$ represent the volume of data that $g_{\rm x}$ plans to offload and the volume of data which is actually offloaded by $g_{\rm x}$ at time slot l, respectively. The first aim of this paper is to maximize the *Throughput Index*, as shown in (7),

$$\text{maximize}\left\{I_{\rm throughput}=\frac{\sum\limits_{g_{\rm x}\in G}\sum\limits_{T_{\rm L}\in T}\sum\limits_{l\in T_{\rm L}}a_{g_x,l}}{\sum\limits_{g_{\rm x}\in G}D_{g_{\rm x}}}\right\}. \quad (7)$$

In addition to the maximal throughput, the fairness is another issue that the BBCO algorithm should take into account. Let $U_{g_{\rm x}}$ denote the total offloaded content volume of the sedan $g_{\rm x}$, which is given by $U_{g_{\rm x}}=\sum_{T_{\rm L}\in T}\sum_{l\in T_{\rm L}}a_{g_{\rm x},l}$. We use the *Service Fairness Index*, which is represented by $I_{\rm fairness}$, to measure the degree of the fairness goal,

$$\text{maximize}\left\{I_{\rm fairness}=\frac{(\sum\limits_{g_{\rm x}\in G}U_{g_{\rm x}})^2}{k\sum\limits_{g_{\rm x}\in G}U_{g_{\rm x}}^2}\right\}, \quad (8)$$

where k is the number of sedans of the observed vehicular networks . It is obvious that both the values of $I_{\rm throughput}$ and $I_{\rm fairness}$ are ranging from 0 to 1. By introducing a weight factor ζ, the two indices could be merged together, and the goal of the paper can be expressed in (9).

Objective function:

$$\textbf{maximize}\ \left\{(1-\zeta)\frac{\sum_{g_x\in G}\sum_{T_L\in T}\sum_{l\in T_L} a_{g_x,l}}{\sum_{g_x\in G} D_{g_x}}+\zeta\frac{(\sum_{g_x\in G} U_{g_x})^2}{k\sum_{g_x\in G} U_{g_x}^2}\right\}. \tag{9}$$

It is a challenging task to develop an optimal algorithm to reach the goal. Since the sedans have different transmission rate at each time slot and the time durations that sedans stay in the coverage of the bus are different from each other. If the offloading algorithm only consider the transmission rate at each time slot or the order that the sedan connects to the bus to set out the offloading schedule, there is a lot of sedans would never get an opportunity to acquire content in their paths. Aiming to solve the above issues, the BBCO algorithm is proposed in this paper to balance the relationship between the maximization of offloaded data volume and offloading opportunity fairness.

Equations (10)–(12) present several constraints for reaching the goal of this paper. Given the VN and the bus b_p travelling a road segment to offer content offloading service for the sedans nearby, one sedan would be selected by the bus to offload content at time slot l, denoted as $g_d^{(l)}$. Let Boolean variable $A_{g_x,l}$ denote whether sedan g_x has offloaded data at time slot l, i.e.,

$$A_{g_x,l}=\begin{cases}1, & g_d^{(l)}=g_x\ \ l\in T_L, x_s\le l\le x_e;\\ 0, & \text{otherwise.}\end{cases} \tag{10}$$

When bus b_p receives data requests from more than one sedan at the same time, it can provide offloading service to at most one sedan at any time slot l. The following constraint reflects this fact.

Unicast Constraint:

$$\sum_{g_x\in G_L} A_{g_x,l}\le 1 \tag{11}$$

The volume of actually offloaded data in time duration T_L should be no more than the volume of the requested data.

Offloading Bound Constraint:

$$0\le\sum_{l\in T_L}(A_{g_x,l}\cdot a_{g_x,l})\le D_{g_x} \tag{12}$$

IV. THE DESIGN OF THE PROPOSED BUS-BASED CONTENT OFFLOADING

The following sections introduce the details of the three phases designed in the BBCO algorithm.

A. Encounter Buses Prediction Phase

Let S_x and Φ_x denote the set of segments and intersections that will be traversed by the sedan g_x in a given duration T. Let segment $s_{i,j}=(I_i,I_j)$ $(s_{i,j}\subseteq S_x)$ denote that segment $s_{i,j}$ consists of two intersections I_i and I_j as its end points. Based on the assumption in system model, each sedan g_x is aware of its own path $S_x(S_x\in S)$ which consists of the traversed road segments in a given duration T. Fig. 3 depicts an example that $S_x=\{s_{1,4},s_{4,2},s_{2,3}\}$. Consider a road segment $s_{i,j}\in S_x$, whereas b_y is a bus that will travel along segment $s_{i,j}$. This paper further assumes that the arrival time of bus b_y to each intersection $I_i(I_i\in\Phi_x)$ is known by each g_x. In addition to that, the navigation system of g_x could record the time when g_x arrives at each intersection of its path. Similar to [23], this paper assumes that the driving time of vehicle over a segment follows the Gamma distribution. The driving time of segment $s_{i,j}$ can be modeled as: $t_{i,j}\sim\Gamma(\beta,\lambda)$, where parameter $1/\lambda$ of the Gamma distribution can be interpreted as a scaling parameter and β denotes the shape parameter of the distribution. To calculate β and λ, we should acquire the mean and variance of $t_{i,j}$, which are the traffic statistical information provided by traffic management department. Note that the models of sedan and bus have different β and λ.

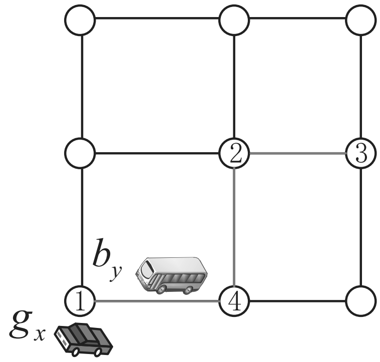

Fig. 3. Sedan g_x and bus b_y will encounter at highway segment s_{14}.

Fig. 3 gives an example of the considered scenario where g_x moves starting from intersection I_1, passing through I_4 and I_2, finally arriving at I_3. Let $t_{g_x,i}$ and $t_{g_x,j}$ be the time when sedan g_x arrivals at intersections I_i and I_j, respectively. Let $t_{b_y,i}$ and $t_{b_y,j}$ be the time when bus b_y arrivals at intersections I_i and I_j, respectively. It is well known that $v(g_x)\gg v(b_y)(g_x\in G, b_y\in B)$.

Let $N_{i,j}^{g_x}$ and $B_{i,j}^{g_x}$ denote the number of buses that encountered by g_x at road segment $s_{i,j}$ and the set of those buses, respectively. Let $b_y\in B_{i,j}^{g_x}$, we have:

$$t_{b_y,i}\le t_{g_x,i}\cap t_{g_x,j}\le t_{b_y,j}. \tag{13}$$

The intersection $A\cap B$ of two sets A and B is the set that contains all elements of A that also belong to B.

Let $t_{i,j}^{g_x}$ and $t_{i,j}^{b_y}$ denote the travel time through $s_{i,j}$ by g_x and b_y, respectively. Based on the derivation of $t_{g_x,j}=t_{g_x,i}+t_{i,j}^{g_x}$ and $t_{b_y,j}=t_{b_y,i}+t_{i,j}^{b_y}$, we have the constraint as shown in (14),

$$t_{g_x,i}+t_{i,j}^{g_x}-t_{i,j}^{b_y}\le t_{b_y,i}\le t_{g_x,i}. \tag{14}$$

Based on (13) and (14), the sedan g_x and the bus b_y would encounter at road segment $s_{i,j}$ if the time meet following conditions,

1. g_x's arrival time of intersection I_i is later than b_y's arrival time of intersection I_i,
2. g_x's leaving time of intersection I_i is earlier than b_y's leaving time of intersection I_i.

Therefore, the number of buses encountered by sedan $g_{\rm x}$ could be calculated as:

$$N^{g_{\rm x}} = \sum_{s_{\rm i,j} \in S_{\rm x}} N^{g_{\rm x}}_{\rm i,j}. \tag{15}$$

In the *EBP phase*, each sedan would record the number of buses which it has met in its trajectory.

B. Transmission Rate Estimation Phase

In this phase, each sedan $g_{\rm x}$ aims to estimate the transmission rate $r_{g_{\rm x}}(l)$ at arbitrarily time slot l when $g_{\rm x}$ maintains connection state with the bus $b_{\rm p}$. First of all, each sedan $g_{\rm x}$ should predict the connection duration $C_{g_{\rm x}}$ which is the time duration that $g_{\rm x}$ stays in the coverage of the bus $b_{\rm p}$. Then, the $g_{\rm x}$ estimate the transmission rate at each time slot among $C_{g_{\rm x}}$. In the environment of multiple lanes, there are two key factors that determine the value of $C_{g_{\rm x}}$: 1) The relative speed between $g_{\rm x}$ and $b_{\rm p}$ and 2) the distance from the lane which is occupied by $g_{\rm x}$ to the lane which $b_{\rm p}$ is driving on. In this paper, the estimation of $C_{g_{\rm x}}$ is based on mobility estimation and prediction method appears in [22]. For simplicity, this paper has two assumptions to restrain the estimation process.

Assumption 1: The sedan $g_{\rm x}$ connects to at most one bus at the same time.

Assumption 2: The sedan $g_{\rm x}$ maintains a uniform velocity among $C_{g_{\rm x}}$.

The more complex situation will be investigated in the near-future.

Initially, $g_{\rm x}$ would broadcast a download request (DR) message at frequency $f_{\rm t}$. The DR message contains the volume of data $D_{g_{\rm x}}$ that $g_{\rm x}$ plans to offload and speed of sedan $v(g_{\rm x})$. Then $g_{\rm x}$ records the time point of this broadcasting. Upon receiving the DR message, the bus $b_{\rm p}$ would respond with an acknowledgement (ACK) message which includes the speed of bus $v(b_{\rm p})$ and the Doppler shift of received signal $f_{\rm dO}$, meanwhile the ACK message would contain the time information to help $g_{\rm x}$ execute time synchronization. The sedan $g_{\rm x}$ would record the time point of receiving the ACK message from $b_{\rm p}$. Finally, $g_{\rm x}$ would send download-acknowledgement (D-ACK) message to bus, which includes the connection time $C_{g_{\rm x}}$, the transmission rate $r_{g_{\rm x}}(l)$ at arbitrarily time slot l and an indication that $b_{\rm p}$ is the $n^{g_{\rm x}}$th bus that $g_{\rm x}$ has met.

Fig. 4 gives an example to illustrate the operations of estimating $C_{g_{\rm x}}$. As shown in Fig. 4, $g_{\rm x}$ has sent a DR message at position A and has received ACK message at position B. The driving time interval ϵ between A and B has been recorded by the $g_{\rm x}$. In fact, the speed of sedan is much larger than the bus, so the relative speed $v(g_{\rm x} \to b_{\rm p})$ of $g_{\rm x}$ and $b_{\rm p}$ can be presented as

$$v(g_{\rm x} \to b_{\rm p}) = v(g_{\rm x}) - v(b_{\rm p}). \tag{16}$$

Therefore, the length of *AB* can be calculated by

$$\overline{AB} = v(g_{\rm x} \to b_{\rm p})\epsilon. \tag{17}$$

Based on the calculation $f_{\rm dO} = (f_{\rm t} v(g_{\rm x} \to b_{\rm p}) \cos\theta)/c$, where c is the speed of light, we have

$$\cos\theta = \frac{c f_{\rm dO}}{f_{\rm t} v(g_{\rm x} \to b_{\rm p})}. \tag{18}$$

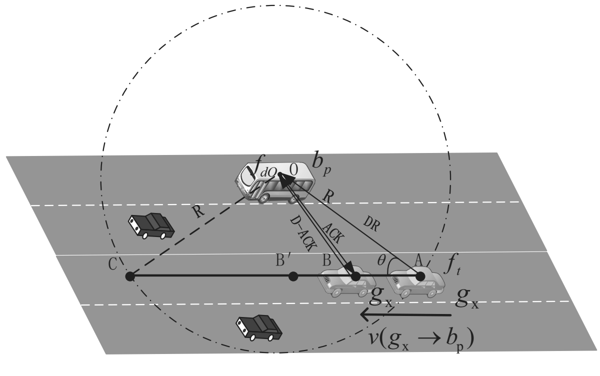

Fig. 4. Sedans predict the connection duration.

Based on (13), $\overline{AC}$ can be presented as

$$\overline{AC} = 2R\cos\theta. \tag{19}$$

From (11)–(14), the connection duration $C_{g_{\rm x}}$ can be derived as

$$C_{g_{\rm x}} = \frac{\overline{AC} - \overline{AB}}{v(g_{\rm x} \to b_{\rm p})} = \frac{2R\cos\theta - (v(g_{\rm x}) - v(b_{\rm p}))\,\epsilon}{v(g_{\rm x}) - v(b_{\rm p})}. \tag{20}$$

Based on the assumptions made in system model, $C_{g_{\rm x}} = [x_{\rm s}, x_{\rm e}](x_{\rm s} \geq 1, g_{\rm x} \in G_{\rm L})$, we have

$$x_{\rm e} - x_{\rm s} + 1 = \frac{C_{g_{\rm x}}}{\tau}, \tag{21}$$

where $x_{\rm s}$ is the first time slot that $g_{\rm x}$ could offload data from $b_{\rm p}$. At the time slot l ($x_{\rm s} \leq l \leq x_{\rm e}$), the length of the path which travelled by the sedan $g_{\rm x}$ can be calculated by

$$\overline{AB_l} = \overline{AB} + \tau(l - x_{\rm s})v(g_x). \tag{22}$$

Therefore, the distance between $g_{\rm x}$ and $b_{\rm p}$ at time slot l, which is denoted as $d_{g_{\rm x},l}$, can be derived as

$$d_{v_{\rm x},l} = \begin{cases} \sqrt{R^2 + \overline{AB_l}^2 - 2R\overline{AB_l}\cos\theta}, & x_{\rm s} \leq l \leq x_{\rm e}; \\ \infty, & otherwise. \end{cases} \tag{23}$$

Based on the system model, the transmission rate $r_{g_{\rm x}}(l)$ of the sedan $g_{\rm x}$ at each time slot l could be derived. After the calculative process, the sedan $g_{\rm x}$ would send D-ACK message to the bus $b_{\rm p}$.

C. Time Slots Allocation Phase

In the above two phases, the estimated values will be sent to bus $b_{\rm p}$. In this phase, $b_{\rm p}$ aims to formulate a time slot allocation scheme based on the DR and D-ACK messages which received from multiple sedans. The bus $b_{\rm p}$ would formulate the profit matrix as (24) at each time slot because that some sedans leave and some other sedans enter. The transmission rate of each sedan would also change with the varied headway distance between vehicles. We could derivate the profit matrix at time slot

$l (l \in T_{\mathrm{L}})$ as follows

$$P_{g_{\mathrm{x}}}^{(l)} = \begin{cases} r_{g_{\mathrm{x}}}(l), & l \in [x_{\mathrm{s}}, x_{\mathrm{e}}],\ D_{g_{\mathrm{x}}} - u_{g_{\mathrm{x}}} \geq r_{g_{\mathrm{x}}}(l); \\ D_{g_{\mathrm{x}}} - u_{g_{\mathrm{x}}}, & l \in [x_{\mathrm{s}}, x_{\mathrm{e}}],\ 0 < D_{g_{\mathrm{x}}} - u_{g_{\mathrm{x}}} \leq r_{g_{\mathrm{x}}}(l); \\ 0, & \text{otherwise}, \end{cases} \tag{24}$$

where $u_{g_{\mathrm{x}}}$ denotes the offloaded volume of the sedan, $u_{g_{\mathrm{x}}} = \sum_{j=1}^{l} A_{g_{\mathrm{x}},j} a_{g_{\mathrm{x}},j}$.

We notice that there might be multiple sedans send their DR and D-ACK messages to bus b_{p} at same time slot. Based on the profit matrix and the received D-ACK messages, b_{p} would derive *Selection Function* to select a sedan to offer data offloading service at the arbitrary time slot l, which is denoted as $g_{\mathrm{d}}^{(l)}$,

$$g_{\mathrm{d}}^{(l)} = \max_{g_{\mathrm{x}} \in G_{\mathrm{L}}} \left\{ (1-\alpha) \frac{P_{g_{\mathrm{x}}}^{(l)}}{r^{\mathrm{ideal}}} + \alpha \frac{n^{g_{\mathrm{x}}}}{N^{g_{\mathrm{x}}}} \right\} \quad l \in T_{\mathrm{L}}, \tag{25}$$

where α is a weighting factor and r^{ideal} is the ideal transmission rate according to Shannon theorem. $n^{g_{\mathrm{x}}}$ is the number of the offloading bus which the sedan g_{x} has met in its trajectory. Since the opportunity of encountering the other buses in the future path is decreased with the increased value of $n^{g_{\mathrm{x}}}/N^{g_{\mathrm{x}}}$. The high value of $n^{g_{\mathrm{x}}}/N^{g_{\mathrm{x}}}$ means that the content requests of these sedans are very urgent, then the BBCO algorithm would give the urgent sedan higher priority to guarantee fairness by adaptively adjust the value of α.

The detailed BBCO algorithm is presented in Algorithm 1, which consists of three phases. Phases I and II are mainly executed by sedan while phase III is mainly applied by bus. Firstly, in the *EBP phase*, each sedan performs step 1 to predict the number of encountered buses. After that, the *TRE phase* will be executed when g_{x} encounters the bus. Each g_{x} executes steps 2 to 5, which estimate the connection duration $C_{g_{\mathrm{x}}}$ and the transmission rate $r_{g_{\mathrm{x}}}(l)$. Finally, the *TSA phase* is performed by bus b_{p}. In this phase, bus b_{p} applies steps 6 to 11, which allocate the T_{L} time slots to the sedans.

By applying the BBCO algorithm for segment $s_{\mathrm{i,j}}$, the volume of offloaded data, denoted as $W_{s_{\mathrm{i,j}}}$, can be derived by (26),

$$W_{s_{\mathrm{i,j}}} = \sum_{l=1}^{T_{\mathrm{L}}} P_{g_{\mathrm{d}}^{(l)}}^{(l)}. \tag{26}$$

The service fairness index can be further evaluated by (27),

$$I_{\mathrm{fairness}} = \frac{\left(\sum_{g_{\mathrm{x}} \in G_{\mathrm{L}}} \left(\frac{\sum_{j \in T_{\mathrm{L}}} A_{g_{\mathrm{x}},j} \cdot a_{g_{\mathrm{x}},j}}{D_{g_{\mathrm{x}}}} \right) \right)^2}{k \sum_{g_{\mathrm{x}} \in G_{\mathrm{L}}} \left(\frac{\sum_{j \in T_{\mathrm{L}}} A_{g_{\mathrm{x}},j} a_{g_{\mathrm{x}},j}}{D_{g_{\mathrm{x}}}} \right)^2}. \tag{27}$$

In given time duration, each bus $b_{\mathrm{y}} \in B$ moving along a road segment $s_{\mathrm{i,j}} \in S$ would allocate the time slots to sedans. Both the throughput and fairness issues have been considered and the values are obtained by applying (26) and (27).

Algorithm 1 *Bus-Based Content Offloading*

Input: The number of time slots T_{L}, the volume of data $D_{g_{\mathrm{x}}}$ that sedan g_{x} plans to offload.
Output: Allocate T_{L} time slots to the sedans.

Phase I: *Encounter Buses Prediction Phase*
1. Each sedan g_{x} predicts the number of encountered buses $N^{g_{\mathrm{x}}}$ by applying Exp. (15);

Phase II: *Transmission Rate Estimation Phase*
2. Each g_{x} broadcasts a DR message;
3. Upon receiving the DR message, the bus b_{p} replies with an ACK message;
4. Each g_{x} calculates the connection duration $C_{g_{\mathrm{x}}}$ with bus and the transmission rate $r_{g_{\mathrm{x}}}(l)$ at time slot l by applying (20) and (6), repectively;
5. After derived $C_{g_{\mathrm{x}}}$ and $g_{g_{\mathrm{x}},l}$, the sedan g_{x} sends the D-ACK message to bus b_{p};

Phase III: *Time Slots Allocation Phase*
6. Based on the received message, bus b_{p} would initialize the profit matrix $P_{g_{\mathrm{x}}}^{(1)}$ at the first time slot as (24);
7. The bus b_{p} would select an sedan to offer data offloading service at the first time slot as (25);
8. **for** $l > 1 (l \in T_{\mathrm{L}})$ **do**
9. The b_{p} would update the profit matrix at the end of each time slot as (24);
10. Apply a *Selection Function* (25) to allocate the lth time slot to a sedan $g_{\mathrm{d}}^{(l)}$.
11. **end for**

/* formulate a solution to time slots allocation*/

V. PERFORMANCE EVALUATION

This section compares the performance of the BBCO algorithm with the *greedy-based offloading algorithm (GBOA)* [24] and the *sequence-based offloading algorithm (SBOA)* [25]. The GBOA selects the sedan to offload content with the maximal transmission rate at each time slot while the SBOA applies the policy that the earlier connected sedan would has the higher offloading priority.

Matlab is the simulation tool that we used in this paper. Our experiments are the theoretical performance evaluation based on the numerical calculations. We consider a vehicular network consisting of 10 to 80 sedans randomly distributed along a pre-defined segment. The major parameters for simulation are shown in Table 2. The performances of the three compared algorithms are measured in terms of throughput that the volume of offloaded data and service fairness index in T_{L} time slots.

A. *Impact of the Sedan's Density*

Figs. 5 and 6 show service fairness index and throughput for different offloading algorithms, as a function for the number of sedans ranging from 10 to 80. As shown in Fig. 5, the BBCO algorithm outperforms GBOA and SBOA in all cases. The results indicate that more sedans have got the offloading opportunities. Since the number of buses which g_{x} will encounter in its path is taken into account as shown in (27), BBCO algorithm will give a higher priority to the sedan which has urgent content request. The degree of fairness has positive correlations with the number of sedans that have offloaded data from the bus.

Fig. 6 compares the three algorithms in terms of throughput. The BBCO algorithm considers both fairness and throughput simultaneously, so the selected sedan may not has the maximum transmission rate at each time slot, which may sacrifice the throughput slightly. However, as shown in Fig. 6, the performance of BBCO algorithm is slightly worse than GBOA which

Table 2. Reference value for main parameters.

Parameter	Description	Value
L	Length of the pre-defined segment	800 m
$v(b_{\mathrm{p}})$	Speed of the bus b_{p}	30 km/h
τ	Duration of one time slot	1 s
R	V2V communication range	200 m
P_t	The transmission power	200 mW
δ	The thermal noise power	10^{-8} mW
$D_{g_{\mathrm{x}}}$	The requested volume of data for g_{x}	50 – 500 Mb

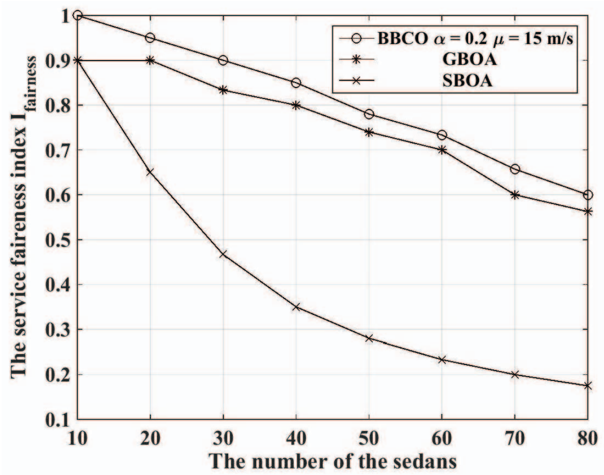

Fig. 5. The service fairness index I_{fairness} vs. sedan's density.

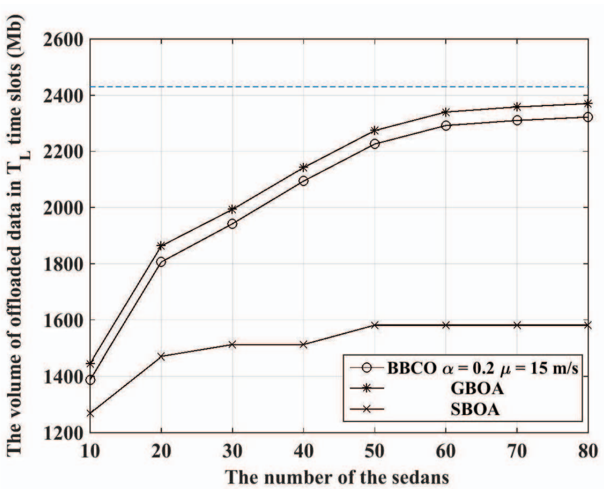

Fig. 6. The volume of offloaded data vs. sedan's density.

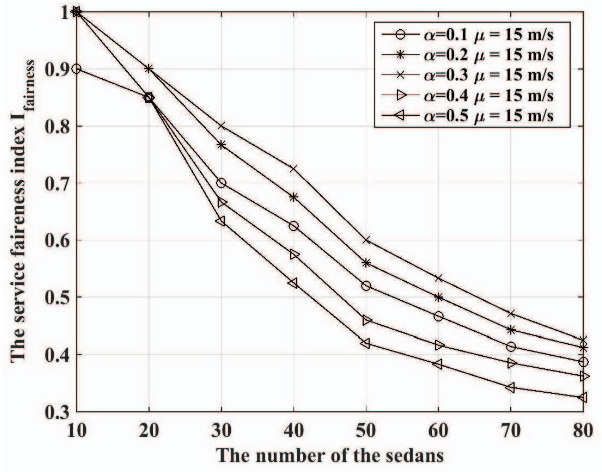

Fig. 7. The service fairness index I_{fairness} vs. weight factor.

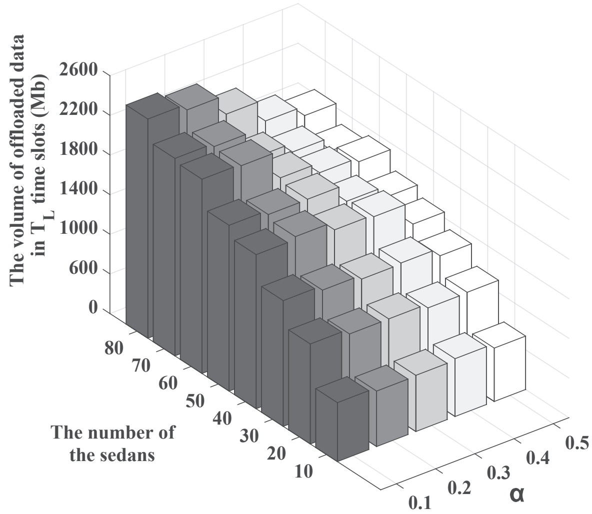

Fig. 8. The volume of offloaded data vs. weight factor, when $\mu = 15$ m/s.

has the maximum throughput. Moreover, with the increase of sedan's density, the throughput is getting closer to the system capacity which is represented as the imaginary line.

B. Impact of the Weight Factor

Recall that both the two parameters, including the volume of offloaded data and the number of buses which the sedan would encounter in its future path, have been considered in (27). Fig. 7 investigates the impacts of the two parameters on the performance of BBCO algorithm, when the value of α is ranging from 0.1 to 0.5 and the average speed of the sedans μ is 15 m/s. As shown in Fig. 7, the service fairness index is increased with α when α is ranging from 0.1 to 0.3. This policy leads to the situation that those sedans which has urgent content request will have a priority to offload data. However, when α exceeds 0.3, the urgency factor obtains a significant weight. This weight results in an excessive offloading priority to the sedans which have urgent content request. Consequently, the service fairness index shows a worse performance than the situation when α is less than 0.3.

Fig. 8 investigates the performance impacted by the parameters including α and the density of sedan. As shown in Fig. 8, for network scenarios with larger α, which resulted in a decline in the volume of offloaded data in T_{L} time slots. This occurs because that the selected sedan which has a urgent data request may not has the maximal throughput at each time slot.

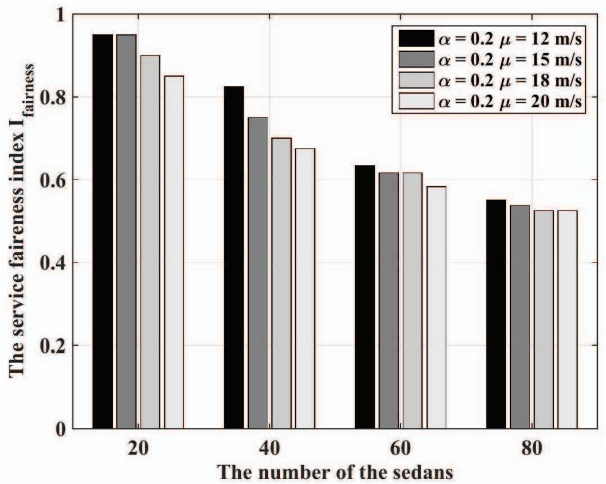

Fig. 9. The service fairness index I_{fairness} vs. sedan's speed.

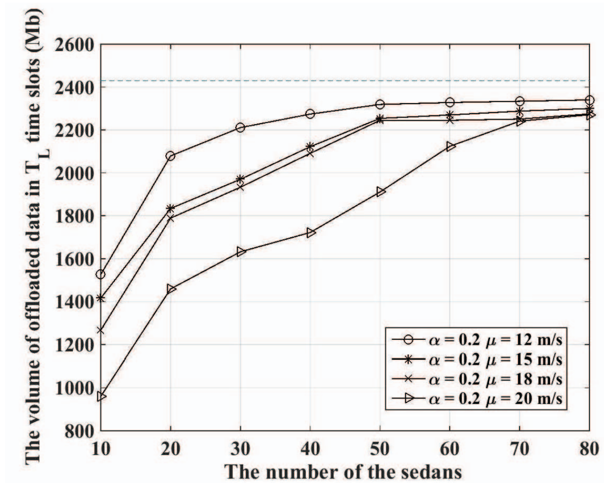

Fig. 10. The volume of offloaded data vs. sedan's speed.

C. Impact of the Sedan's Speed

Fig. 9 shows the simulation results of the service fairness index for different average speed. When μ is relatively low, the BBCO algorithm provides a more fair offloading service than the high-speed scenario. For example, when $\mu = 12$ m/s, the I_{fairness} is always bigger than other high-speed scenario at different sedan's density. This is due to the fact that the sedan with low speed has a longer connection duration with the bus, which helps the sedan get more offloading opportunities. As a result, the I_{fairness} decreases with the moving speed of the sedan, as shown in Fig. 9.

Next, we examine the effect of different average speed on the volume of the offloaded data in Fig. 10. Comparing the simulation results obtained for the same α but different μ, the volume of offloaded data decreases with μ. This is because a higher speed of the sedan could lead to the short connection duration, so the volume of offloaded data is affected negatively. Moreover, when the sedan is moving at a low speed (e.g., $\mu = 12$ m/s), the volume of offloaded data would be closer to system capacity. From the above two figures, we could demonstrate that the performance of BBCO algorithm is mainly affect by the speed of the sedan.

VI. CONCLUSIONS

In this paper, we focus on content offloading schedule in VANETs, which a bus traveling along the pre-defined highway segments aims to provide content offloading service. The maximal data volume and fair offloading opportunity are considered. The BBCO algorithm mainly consists of three phases. Initially, in *EBP phase*, each sedan predicts the number of buses which will be encountered in its path and record the number of buses which it has met. Then, in *TRE phase*, the connection duration with the bus and the transmission rate at each time slot are estimated by each sedan. Finally, in *TSA phase*, the bus establishes the profit matrix and formulates a *Selection Function* based on the above studies to select a sedan to offload content from bus at each time slot. Simulation results demonstrate that the proposed algorithm likely maximizes the volume of offloaded data and guarantees offloading opportunity fairness.

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