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Optimization-Oriented Resource Allocation Management for Vehicular Fog Computing

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ABSTRACT Vehicular fog computing, which extends the mobile cloud paradigm, is usually composed of stable infrastructures, a large volume of vehicles, portable devices, and robust networks. As a service-providing platform, it is significant to quickly obtain the required service with the aim to correctly save the energy of the corresponding nodes and effectively improve the network survivability. However, the limited capacity of components makes such a situation more complicated. This paper aims to reduce serving time by allocating the available bandwidth to four kinds of services. A utility model is built according to the above-mentioned serving methods and is solved through a two-step approach. For the first step, all the sub-optimal solutions are provided based on a Lagrangian algorithm. For the second step, an optimal solution selection process is presented and analyzed. A numerical simulation is executed to illustrate the allocation results and the optimal utility model while optimizing the survivability.

INDEX TERMS Bandwidth allocation, vehicular fog computing, survivability optimization, utility.

I. INTRODUCTION

Vehicular network is attracting increasing attention from both academia and industry due to the emerging technologies in wireless communications, intelligent manufacturing, and other related fields. It holds a promising future to integrate social activities [1], traffic management [2], energy supply [3], and so on, with the transportation system. Such combination requires more powerful networks to link substantial infrastructures, a large volume of vehicles, and portable devices. Different from the static access pattern in the first Internet, participants in a vehicular network prefer to achieve data exchanges when they are moving along the road. Both the neighbor vehicles and Road Side Units (RSUs) can be leveraged to extend the signal coverage and process capacity significantly. Driven by the merits of Mobile Ad-hoc Networks (MANETs) and existing requirements of traffic areas, Vehicular Ad-Hoc Networks (VANETs) have been proposed and widely discussed from multiple perspectives. Such evolution can be more progressive when more advanced concepts, such as Social Networks, Big Data, are involved. However, the obstacles (such as Intermittent connectivity [4], dynamic topology [5], and user privacy [6]) are as clear as the benefits during the implementation process. Therefore, providing reliable and effective transmission is a big challenge for the community [7]. Researchers are looking for more novel solutions and paradigms [8], [9].

As a desirable solution, fog computing was firstly proposed in 2012 by Cisco in [10]. Since the beginning, it has been a hot research area [11]–[13]. Fog computing extends cloud computing by adding a new layer between the cloud and its end users [14]–[16]. With fog computing, cloud computing can pre-push specific essential resources to fog and bring down the network latency and meet intensive network access requirements. Thus, lots of services can be deployed in fog computing rather than in cloud computing, such as live streaming, data storing, and online chatting. If fog computing allows the end mobile devices to access, it becomes mobile fog computing. Due to power supply limitations of mobile fog computing devices, the feasibility of this network should be examined. Users prefer to get high-quality services with minimal time consumptions. A possible way is to allocate the available bandwidth according to the service model optimally.

There are two kinds of services, namely: the elastic and the inelastic [17]. Usually, the elastic services are not sensitive to the latency and available bandwidth, while the inelastic

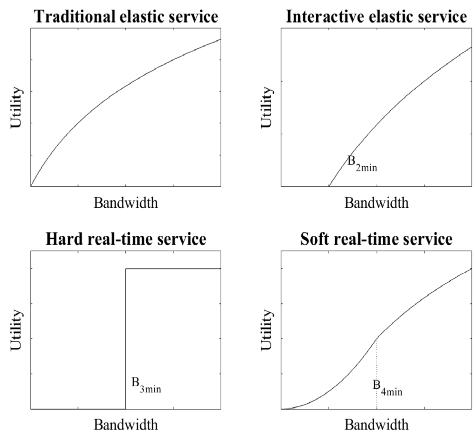

FIGURE 1. **Utility functions of four kinds of services [17].**

services are the opposite [18], [19]. Furthermore, as shown in Figure 1, the elastic services can be divided into traditional elastic services (TESs) (e.g., data transmission) and interactive elastic services (IESs) (e.g., online chatting). The inelastic services can be divided into hard real-time services (HRTSs) (e.g., VoIP) and soft real-time services (SRTSs) (e.g., VoD or living streaming) [20], [21]. The detailed characteristics of these types of services are as follows.

(1) The utility of TESs raises with the increase of available bandwidth in a logarithm pattern, e.g., the data transmission services can be done according to the available bandwidth.

(2) The utility of IESs is a two-stage model. If the available bandwidth is smaller than the threshold value $B_{2,min}$ (shown in Figure 1), the services will fail. Otherwise, the utility will be the same as the utility of the TESs, e.g.. If the available bandwidth is too small, users may not be able to use all the services such as online chatting.

(3) The utility of HRTSs takes after the utility of IESs. One difference is that if the threshold value $B_{3,min}$ (shown in Figure 1) is met, the utility does not change with the increase of bandwidth, e.g., if the bandwidth is more significant than the minimum value, the quality of VoIP will not be changed.

(4) The utility of SRTSs is also a two-stage model. If the offered bandwidth is smaller than the given bandwidth threshold value $B_{4,min}$ (shown in Figure 1), the utility of TESs will increase with the amount of the available bandwidth in an exponential pattern. Otherwise, the utility will be the same as the utility of TESs, e.g., the quality of live streaming increases dramatically when the available bandwidth increases in the range of [0, threshold]. Meanwhile, it increases slowly when the available bandwidth is in the range of [threshold, $+\infty$].

Each service needs sufficient bandwidth to execute the assigned tasks. However, the total available bandwidth is limited. So, the optimal allocation of the available bandwidth among four kinds of services is a crucial research point. In this paper, the network utility is used as a measuring index to allocate the available bandwidth. Firstly, the vehicular fog computing utility model is built according to the serving model in which the cloud, fog and users form a serving unit. Fog gets serving resources from the cloud, stores essential outcomes in the cloud, and offers services to end users. This paper mainly focuses on the third function. Each service has a unique utility function affected by the offered amount of bandwidth. It is possible to get the integral vehicular fog computing utility model summing up the four weight utilities. Then, the optimization of the utility model is carried out. It is divided into two steps. First of all, the total available bandwidth is assumed being optimally allocated. As there are four kinds of services with three singular points, the bandwidth allocation scheme has eight possibilities. In each case, by optimizing the utility function, we can get the allocated bandwidth of each service. Then, according to each possibility constraint, the range of total available bandwidth can be obtained. Some of the ranges may be overlapped. As a consequence, all the possible allocations are sub-optimal ones. In the second step, the actual total available bandwidth is divided into successive smaller ranges according to the ranges obtained in the first step. In each small range, all the possible utilities are calculated. Subsequently, the maximum one is chosen. This process can make the sub-optimal allocation turn to be an optimal one. Eventually, all the optimal allocations are connected and the optimal utility model is gotten for the vehicular fog computing.

This paper is organized as follows. In Section 2, we briefly summarize the works of literature related to our approach. In Section 3, the problem formulation is presented, and the utility model is built. Section 4 solves the proposed model and Section 5 presents numerical simulations to show how the bandwidth allocation scheme works. Finally, the entire work is concluded in Section 6.

II. RELATED WORKS

Vehicular fog computing is a new paradigm. Although researchers have focused on many aspects, this paper aims to investigate the issues in resources allocations management. Several representative works of literature are listed and discussed in below.

From the vehicular perspective, Han *et al.* [22] presented a coexistence issue when portable devices and fixed equipment appear simultaneous. Due to the limitations of transmitting power, it is necessary to coordinate resource usages among users. The coexistence problem was converted into a nonlinear programming problem and three different algorithms are created. The first one is in charge of obtaining a convex program. The second and third ones are responsible for achieving the final solutions. The performance comparisons are also provided. Zhu *et al.* [23] outlined the traffic offload issues in opportunistic vehicular networks and pointed out that the short period of contact was neglected in most cases. By combining the superiority of multiple networks, a data offloading platform was presented. The authors utilized a framework to optimize the resource allocation based on contact period considerations. Simulation results are illustrated to validate

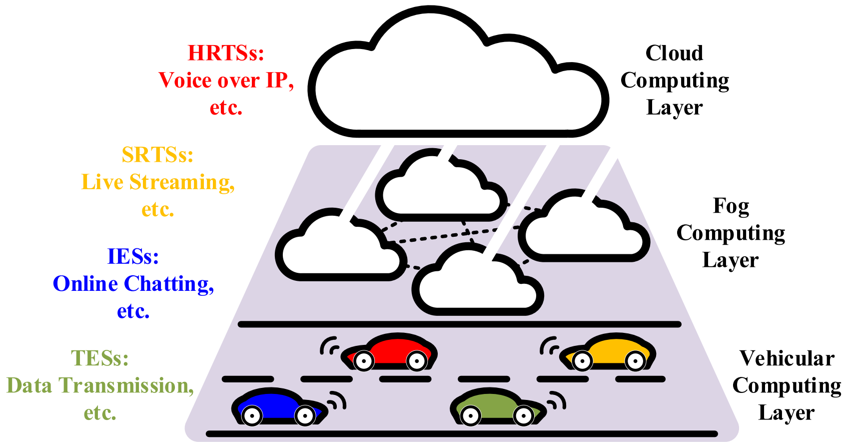

FIGURE 2. Vehicular fog computing serving model.

the effectiveness of the scheme. Mei *et al.* [24] focused on optimizing the energy allocation, radio spectrum and coding mechanism in vehicle to vehicle scenarios. The requirements of vehicular clients and cellular clients, regarding latency and reliability, was targeted. Necessary transformations were executed to guarantee if the proposed mathematical problem is solvable. Binary search and Lagrange dual decomposition are adopted to seek the final value. The interference reduction are analyzed based on simulation results. Yang *et al.* [25] investigated the outdated Channel State Information (CSI) feedback and designed a resource allocation policy. An optimization problem was established to improve the secrecy rate. The solution of integer nonlinear programming is the primary support for this paper. A suboptimal algorithm was proposed, and validation results are provided to illustrate the performance of the policy.

From the fog computing perspective, fog computing is a processing the computing at network edge. So the architecture of it is almost the same as edge computing [13]. Two large research areas attract lots of attention, namely security [26]–[28] and resource allocation [29]–[32]. Here we just view some representative works of resource allocation. Zhang *et al.* [29] studied computing resource allocation in fog networks. The network environment is presented as follows. The service operators, namely DSOs, control a set of fog nodes to provide services to subscribers, namely DSSs. The target is to find a method to optimally share the available computing resources of nodes with whole DSSs. They proposed a joint optimization scheme in a distributed fashion. Stackelberg game model is used to solve DSOs pricing and DSSs resource allocation problems. Then, the many-to-many matching game theory is used to solve the matching problem between fog nodes and DSSs. They claimed that the proposed framework could improve the performance of fog computing network remarkably. This network environment and the problem are similar to ours. However, our scheme focuses on the bandwidth allocation among four kinds of services. Deng *et al.* [30] investigated on task management in cloud-based fog computing to optimize power consumption and network delay. The framework is the same as ours, i.e., fog computing adds a fog layer between end users and the cloud. The problem is how to optimally allocate the workload to minimize power consumption when the service delay is minimized. The solving procedures of this problem are divided into three parts. They claimed that this scheme could minimize bandwidth consumption and reduce transmission latency. The problem and solving methods are different from ours. Wang *et al.* [31] studied the computation offloading and the resource allocation by utilizing edge computing mechanisms. They formed an optimal scheme to solve the following problems: resource allocation, computation offloading and content caching. The problem is solved using distributed convex optimization theory. Under different system parameters, the proposed framework can work effectively. The network environment is similar to other papers which uses a fog layer to improves user experiences. Ma *et al.* [32] studied the image restoration in edge computing. They proposed that the image restoration could be processed in the edge server which could shit the load end devices.

From the contents above, we arrive at the following summaries: (1) Most current schemes in vehicular networks did not consider the service difference. (2) Most current schemes in fog computing only focus on the general environment and the optimization ability can be further improved. (3) To the best of our knowledge, there is no work studying the resource allocation via four kinds of services mentioned above in vehicular fog computing area.

III. THE BANDWIDTH ALLOCATION MODEL

In this section, we first introduce how vehicular fog computing works. Then we mainly focus on how to build the bandwidth allocation model according to the serving model.

As depicted in Figure 2, there are three layers in vehicular fog computing architecture: cloud computing layer, fog computing layer and vehicular computing layer. The fog computing layer is at the edge of the network. It can provide local service for users with shorter latency and broader bandwidth. The cloud computing layer can pre-schedule the required resources into fog computing layer to further enhance its ability. The vehicular computing layer can contact with fog computing layer directly with wireless modes. The services can be classified into two categories: inelastic services (HRTSs and SRTSs) and elastic services (IES and TESs). All the services need various bandwidth to execute tasks effectively.

To build the utility model of vehicular fog computing services from a bandwidth perspective, we introduce several necessary notations related to the architecture in table 1.

TABLE 1. **Notation in bandwidth allocation model in vehicular fog computing.**

Symbol	Notation
S	The kinds of services set
B	The offered bandwidth by the vehicular fog computing platform
i	TES($i=1$), IES($i=2$), HRTS($i=3$), SRTS($i=4$)
B_i	The bandwidth of the i'th kinds of services actually allocated
α_i	The utility weight factor for the i'th kinds of services
U_i	The utility of a unit of function of the i'th kinds of services
$U_i(\bullet)$	The utility function of the i'th kinds of services

According to the vehicular fog computing serving model, the utility model (**P1**) of vehicular fog computing platform can be described as follows:

$$\text{P1:} \quad \text{Max } U = \sum_{i=1}^{4} \alpha_i U_i(B_i). \tag{1}$$

$$\text{Subject to } \sum_{i=1}^{4} B_i \leq B. \tag{2}$$

Over

$$\alpha_i \geq 0, \quad sum(\alpha_i) = 1, \; B_i \geq 0. \tag{3}$$

Huang *et al.* [17], Hande *et al.* [18], Lee *et al.* [19], Song *et al.* [20], and Shi *et al.* [21] proposed that the utility functions of TES, IES, HRTS and SRTS are similar as follows:

$$U_1(B_1) = U_1 \log(B_1+1). \tag{4}$$

$$U_2(B_2) = U_2 \log \frac{B_2}{B_{2,min}} \frac{sgn(B_2 - B_{2,min})+1}{2}. \tag{5}$$

$$U_3(B_3) = U_3 \frac{sgn(B_3 - B_{3,min})+1}{2}. \tag{6}$$

$$U_4(B_4) = U_4 \begin{cases} \frac{\log B_{4,min}}{B_{4,min}^2} B_4^2 & B_4 < B_{4,min} \\ \log B_4 & B_4 \geq B_{4,min}. \end{cases} \tag{7}$$

IV. SOLUTIONS TO THE BANDWIDTH ALLOCATION MODEL

In this section, we will solve the model proposed in section 3. Due to utility functions (5), (6) and (7) being segmented, the process is divided into two steps. In the first stage, the total bandwidth B is set as a constant value. Assuming the allocated bandwidth B_1, B_2, B_3, and B_4 fall into a certain set solving the optimization problem. By using the range of B_1, B_2, B_3, and B_4, the range of B can be obtained. In the second stage, the actual B is divided into a smaller range according to the range of B obtained in the first stage. Then, the utility of the cases will be calculated and the ones are falling into the smaller range will be identified. The one with the highest utility is chosen as the optimal one.

In the first step, the solution process can be divided into eight sub-optimal problems.

Case 1) when the allocated bandwidth is subjected to the following assumption:$B_2 \geq B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 \geq B_{4,min}$, we can conclude that the optimal B_3 should be $B_{3,min}$ and the maximum utility is U_3. Then, the optimal problem can be written as follows:

$$U = \alpha_1 U_1 \log(B_1+1) + \alpha_2 U_2 log \frac{B_2}{B_{2,min}} + \alpha_3 U_3 + \alpha_4 U_4 \log(B_4). \tag{8}$$

To solve this optimal problem, the Lagrangian approach is used. The Lagrangian of (8) is:

$$L(B_1, B_2, B_3, B_4; \lambda) = U + \lambda(\Sigma_{i=1}^4 B_i - B). \tag{9}$$

The derivation of each variate in (9) is

$$\begin{cases} L_{B_1} = \alpha_1 U_1/(B_1+1) + \lambda = 0 \\ L_{B_2} = \alpha_2 U_2/B_2 + \lambda = 0 \\ L_{B_4} = \alpha_4 U_4/B_4 + \lambda = 0 \\ B_1 + B_2 + B_3 + B_4 = B. \end{cases} \tag{10}$$

Solving (10), the optimal values of B_1, B_2, B_3, and B_4 are

$$\begin{cases} B_1 = (\alpha_1 U_1)(B - \upsilon)/\tau_1 - 1 \\ B_2 = (\alpha_2 U_2)(B - \upsilon)/\tau_1 \\ B_3 = B_{3,min} \\ B_4 = (\alpha_4 U_4)(B - \upsilon)/\tau_1. \end{cases} \tag{11}$$

$\tau_1 = \alpha_1 U_1 + \alpha_2 U_2 + \alpha_4 U_4$, $\upsilon = B_{3,min} - 1$

A point that we should pay attention to is that the obtained values of B_1, B_2, B_3, and B_4 should fit the front assumptions $B_1 \geq 0, B_2 \geq B_{2,min}, B_3 \geq B_{3,min}$, and $B_4 \geq B_{4,min}$ which are

$$\begin{cases} B_1 \geq 0 \\ B_2 \geq B_{2,min} \\ B_3 = B_{3,min} \\ B_4 \geq B_{4,min}. \end{cases} \tag{12}$$

Solving (12), it is possible to evaluate if the optimal value falls into (11), considering the original total vehicular fog computing bandwidth B as:

$$B \geq max \begin{Bmatrix} \tau_1/(\alpha_1 U_1) + \upsilon, \\ \tau_1 B_{2,min}/(\alpha_2 U_2) + \upsilon, \\ B_{3,min}, \\ \tau_1 B_{4,min}/(\alpha_4 U_4) + \upsilon \end{Bmatrix}. \tag{13}$$

Case 2) when the allocated bandwidth is subjected to the following assumption: $B_2 \geq B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 < B_{4,min}$, we can conclude that the optimal B_3 should be

$B_{3,min}$ and the maximum utility is also U_3. Then, the optimal problem can be written as follows:

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_2 U_2 log \frac{B_2}{B_{2,min}} + \alpha_3 U_3 + \tau_2 B_4^2. \quad (14)$$

$\tau_2 = \alpha_4 U_4 (\log B_{4,min}/B_{4,min}^2)$

Even in this case, to solve the optimal problem, the Lagrangian approach is used. The Lagrangian of (14) is:

$$L(B_1, B_2, B_3, B_4; \lambda) = U + \lambda(\Sigma_{i=1}^4 B_i - B). \quad (15)$$

The derivation of each variate in (15) is:

$$\begin{cases} L_{B_1} = \alpha_1 U_1/(B_1 + 1) + \lambda = 0 \\ L_{B_2} = \alpha_2 U_2/B_2 + \lambda = 0 \\ L_{B_4} = 2\tau_2 B_4 + \lambda = 0 \\ B_1 + B_2 + B_3 + B_4 = B. \end{cases} \quad (16)$$

Solving (16), the optimal values of B_1, B_2, B_3, and B_4 are:

$$\begin{cases} B_1 = (\alpha_1 U_1)/(\tau_3 + \sqrt{\tau_4}) - 1 \\ B_2 = (\alpha_2 U_2)/(\tau_3 + \sqrt{\tau_4}) \\ B_3 = B_{3,min} \\ B_4 = (\tau_3 + \sqrt{\tau_4})/(2\tau_2). \end{cases} \quad (17)$$

or

$$\begin{cases} B_1 = (\alpha_1 U_1)/(\tau_3 - \sqrt{\tau_4}) - 1 \\ B_2 = (\alpha_2 U_2)/(\tau_3 - \sqrt{\tau_4}) \\ B_3 = B_{3,min} \\ B_4 = (\tau_3 - \sqrt{\tau_4})/(2\tau_2). \end{cases} \quad (18)$$

$\tau_3 = \tau_2(B + 1 - B_{3,min})$, $\tau_4 = \tau_3^2 - 2\tau_2(\alpha_1 U_1 + \alpha_2 U_2)$

Equations (17) and (18) are both possible solutions, subjected to the actual values of the mentioned parameters.

As mentioned previously, the obtained values of B_1, B_2, B_3, and B_4 should fit the front assumptions $B_1 \geq 0$, $B_2 \geq B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 < B_{4,min}$

A) when the solution is (17), we can obtain:

$$\begin{cases} B_1 \geq 0 \\ B_2 \geq B_{2,min} \\ B_3 = B_{3,min} \\ B_4 < B_{4,min}. \end{cases} \quad (19)$$

Solving (19), we can get if the optimal value falls into (17), considering the original total vehicular fog computing bandwidth B as:

$$B = B_{21}^1 \bigcap B_{21}^2 \bigcap B_{21}^4. \quad (20)$$

where

$$B_{21}^1 = \left[\begin{matrix} \sqrt{2\tau_5}/\tau_2 + \upsilon \\ min \left\{ \begin{matrix} \alpha_1 U_1/\tau_2 + \upsilon, \\ \dfrac{(\alpha_1 U_1)^2 + 2\tau_5}{2\alpha_1 U_1 \tau_2} + \upsilon \end{matrix} \right\} \end{matrix} \right],$$

$$B_{21}^2 = \left[\begin{matrix} \sqrt{2\tau_5}/\tau_2 + \upsilon \\ min \left\{ \begin{matrix} \alpha_2 U_2/(\tau_2 B_{2,min}) + \upsilon, \\ \dfrac{(\alpha_2 U_2/B_{2,min})^2 + 2\tau_5}{2\alpha_2 U_2 \tau_2/B_{2,min}} + \upsilon \end{matrix} \right\} \end{matrix} \right],$$

$$B_{21}^4 = \left[\begin{matrix} \sqrt{2\tau_5}/\tau_2 + \upsilon \\ min \left\{ \begin{matrix} 2B_{4,min} + \upsilon, \\ \dfrac{\alpha_1 U_1 + \alpha_2 U_2}{2\tau_2 B_{4,min}} + B_{4,min} + \upsilon \end{matrix} \right\} \end{matrix} \right].$$

$\tau_5 = \tau_2(\alpha_1 U_1 + \alpha_2 U_2)$

B) when the solution is (18), we can get

$$\begin{cases} B_1 \geq 0 \\ B_2 \geq B_{2,min} \\ B_3 = B_{3,min} \\ B_4 < B_{4,min}. \end{cases} \quad (21)$$

Solving (21), we can get if the optimal value falls into (18), considering the original total vehicular fog computing bandwidth B as:

$$B = B_{22}^1 \bigcap B_{22}^2 \bigcap B_{22}^4. \quad (22)$$

where

$$B_{22}^1 = [\sqrt{2\tau_5}/\tau_2 + \upsilon, \alpha_1 U_1/\tau_2 + \upsilon] \bigcup \left[max \left\{ \begin{matrix} \sqrt{2\tau_5}/\tau_2 + \upsilon, \\ \dfrac{(\alpha_1 U_1)^2 + 2\tau_5}{2\alpha_1 U_1 \tau_2} + \upsilon, \alpha_1 U_1/\tau_2 + \upsilon \end{matrix} \right\}, \infty\right)$$

$$B_{22}^2 = [\sqrt{2\tau_5}/\tau_2 + \upsilon, \frac{\alpha_2 U_2}{\tau_2 B_{2,min}} + \upsilon] \bigcup \left[max \left\{ \begin{matrix} \sqrt{2\tau_5}/\tau_2 + \upsilon, \\ \dfrac{(\alpha_2 U_2/B_{2,min})^2 + 2\tau_5}{2\alpha_2 U_2 \tau_2/B_{2,min}} + \upsilon, \dfrac{\alpha_2 U_2}{\tau_2 B_{2,min}} + \upsilon \end{matrix} \right\}, \infty\right)$$

$$B_{22}^4 = [\sqrt{2\tau_5}/\tau_2 + \upsilon, 2B_{4,min} + \upsilon] \bigcup \left[max \left\{ \begin{matrix} 2B_{4,min} + \upsilon, \sqrt{2\tau_5}/\tau_2 + \upsilon, \\ B_{4,min} + \tau_5/(2B_{4,min}\tau_2^2) + \upsilon \end{matrix} \right\}, \infty\right)$$

Case 3) when the allocated bandwidth follows the following assumption: $B_2 \geq B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 \geq B_{4,min}$, we can conclude that the optimal B_3 should be 0 and the maximum utility is 0. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_2 U_2 log \frac{B_2}{B_{2,min}} + \alpha_4 U_4 \log(B_4). \quad (23)$$

Using the same method in 1), the optimal values of B_1, B_2, and B_4 are the same as (11) and B_3 is 0.

According to $B_1 \geq 0$, $B_2 \geq B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 \geq B_{4,min}$, we can get the vehicular fog computing total bandwidth B fits (13), in which $B_{3,min} = 0$.

Case 4) when the allocated bandwidth follows the following assumption: $B_2 \geq B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 < B_{4,min}$, we can conclude that the optimal B_3 should be 0 and the maximum utility is 0. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_2 U_2 log\frac{B_2}{B_{2,min}} + \tau_2 B_4^2. \quad (24)$$

Using the same method in 2), the optimal values of B_1, B_2, and B_4 are the same as (17) or(18) and B_3 is 0.

According to $B_2 \geq B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 < B_{4,min}$, we can get the vehicular fog computing total bandwidth B fits (20) or (22), in which $B_{3,min} = 0$.

Case 5) when the allocated bandwidth is subjected to the following assumption: $B_2 < B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 \geq B_{4,min}$, we can conclude that the optimal B_2 should be 0 and the maximum utility is 0, and the optimal B_3 should be $B_{3,min}$ and the maximum utility is U_3. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_3 U_3 + \alpha_4 U_4 \log(B_4). \quad (25)$$

In order to solve this optimal problem, the Lagrangian approach is used. The Lagrangian of (25) is

$$L(B_1, B_2, B_3, B_4; \lambda) = U + \lambda(\Sigma_{i=1}^4 B_i - B). \quad (26)$$

The derivation of each variate in (26) is

$$\begin{cases} L_{B_1} = \alpha_1 U_1/(B_1 + 1) + \lambda = 0 \\ L_{B_4} = \alpha_4 U_4/B_4 + \lambda = 0 \\ B_1 + B_2 + B_3 + B_4 = B. \end{cases} \quad (27)$$

By solving (27), the optimal values of B_1, B_2, B_3, and B_4 are

$$\begin{cases} B_1 = \alpha_1 U_1/\tau_6 - 1 \\ B_2 = 0 \\ B_3 = B_{3,min} \\ B_4 = \alpha_4 U_4/\tau_6. \end{cases} \quad (28)$$

$\tau_6 = (\alpha_1 U_1 + \alpha_4 U_4)/(B - \upsilon)$

The obtained values of B_1, B_2, B_3, and B_4 should fit the front assumptions $B_1 \geq 0$, $B_2 < B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 \geq B_{4,min}$, which are:

$$\begin{cases} B_1 \geq 0 \\ B_2 = 0 \\ B_3 = B_{3,min} \\ B_4 \geq B_{4,min}. \end{cases} \quad (29)$$

By solving (29), we can get if the optimal value falls into (28), considering the original total fog computing bandwidth B as:

$$B \geq max \begin{Bmatrix} \frac{\alpha_1 U_1 + \alpha_4 U_4}{\alpha_1 U_1} + \upsilon, \\ \frac{\alpha_1 U_1 + \alpha_4 U_4}{\alpha_4 U_4} B_{4,min} + \upsilon \end{Bmatrix}. \quad (30)$$

Case 6) when the allocated bandwidth follows the following assumption: $B_2 < B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 < B_{4,min}$, we can conclude that the optimal B_2 should be 0 and the maximum utility is 0, and the optimal B_3 should be $B_{3,min}$ and the maximum utility is U_3. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_3 U_3 + \tau_2 B_4^2. \quad (31)$$

In order to solve this optimal problem, the Lagrangian approach is used. The Lagrangian of (31) is

$$L(B_1, B_2, B_3, B_4; \lambda) = U + \lambda(\Sigma_{i=1}^4 B_i - B). \quad (32)$$

The Derivation of each variate in (32) is

$$\begin{cases} L_{B_1} = \alpha_1 U_1/(B_1 + 1) + \lambda = 0 \\ L_{B_4} = 2B_4\tau_2 + \lambda = 0 \\ B_1 + B_2 + B_3 + B_4 = B. \end{cases} \quad (33)$$

By solving (33), the optimal values of B_1, B_2, B_3, and B_4 are

$$\begin{cases} B_1 = \frac{\alpha_1 U_1}{\tau_3 + \sqrt{\tau_3^2 - 2\tau_2\alpha_1 U_1}} - 1 \\ B_2 = 0 \\ B_3 = B_{3,min} \\ B_4 = \frac{\tau_3 + \sqrt{\tau_3^2 - 2\tau_2\alpha_1 U_1}}{2\tau_2}. \end{cases} \quad (34)$$

or

$$\begin{cases} B_1 = \frac{\alpha_1 U_1}{\tau_3 - \sqrt{\tau_3^2 - 2\tau_2\alpha_1 U_1}} - 1 \\ B_2 = 0 \\ B_3 = B_{3,min} \\ B_4 = \frac{\tau_3 - \sqrt{\tau_3^2 - 2\tau_2\alpha_1 U_1}}{2\tau_2}. \end{cases} \quad (35)$$

A) when the solution is (34), the obtained value of B_1, B_2, B_3, and B_4 should fit the front assumptions $B_1 \geq 0$, $B_2 < B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 < B_{4,min}$. The solution is

$$B = B_{61}^1 \bigcap B_{61}^4. \quad (36)$$

where

$$B_{61}^1 = \left[min \begin{Bmatrix} \sqrt{2\tau_2\alpha_1 U_1}/\tau_2 + \upsilon, \\ \alpha_1 U_1/\tau_2 + \upsilon, \\ \alpha_1 U_1/(2\tau_2) + B_{3,min} \end{Bmatrix} \right],$$

$$B_{61}^4 = \left[min \begin{Bmatrix} \sqrt{2\tau_2\alpha_1 U_1}/\tau_2 + \upsilon, \\ 2B_{4,min} + \upsilon, \\ \frac{\alpha_1 U_1}{2\tau_2 B_{4,min}} + B_{4,min} + \upsilon \end{Bmatrix} \right].$$

B) when the solution is (34), the obtained values of B_1, B_2, B_3, and B_4 should also fit the front assumptions $B_1 \geq 0$, $B_2 < B_{2,min}$, $B_3 \geq B_{3,min}$, and $B_4 < B_{4,min}$. The solution is that the original total fog computing bandwidth B should be

$$B = B_{62}^1 \bigcap B_{62}^4. \quad (37)$$

where

$$B_{62}^{1} = [\sqrt{2\alpha_1 U_1}/\sqrt{\tau_2} + \upsilon, \alpha_1 U_1/\tau_2 + \upsilon] \bigcup [max\left\{\frac{\sqrt{2\alpha_1 U_1}}{\sqrt{\tau_2}} + \upsilon, \frac{\alpha_1 U_1}{\tau_2} + \upsilon, \frac{\alpha_1 U_1}{2\tau_2} + B_{3,min}\right\}, \infty)$$

$$B_{62}^{4} = [\sqrt{2\alpha_1 U_1}/\sqrt{\tau_2} + \upsilon, 2B_{4,min} + \upsilon] \bigcup [max\left\{\begin{array}{l}\frac{\sqrt{2\alpha_1 U_1}}{\sqrt{\tau_2}} + \upsilon, 2B_{4,min} + \upsilon, \\ \alpha_1 U_1/(2B_{4,min}\tau_2) + B_{4,min} + \upsilon\end{array}\right\}, \infty)$$

Case 7) when the allocated bandwidth follows the following assumption: $B_2 < B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 \geq B_{4,min}$, we can conclude that the optimal B_2 should be 0 and the maximum utility is 0, and the optimal B_3 should be 0 and the maximum utility is 0. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \alpha_4 U_4 \log(B_4). \quad (38)$$

Using the same method in 5), the optimal values of B_1 and B_4 are the same as (28), and B_2 and B_3 is 0.

According to $B_1 \geq 0$, $B_2 < B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 \geq B_{4,min}$, we can get the fog computing total bandwidth B fits (30), in which $B_{3,min} = 0$.

Case 8) when the allocated bandwidth follows the following assumption: $B_2 < B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 < B_{4,min}$, we can conclude that the optimal B_2 should be 0 and the maximum utility is 0, and the optimal B_3 should be 0 and the maximum utility is 0. Then, the optimal problem can be written as follows

$$U = \alpha_1 U_1 \log(B_1 + 1) + \tau_2 B_4^2. \quad (39)$$

Using the same method in 6), the optimal values of B_1 and B_4 are the same as (34) or (35), and B_2 and B_3 is 0.

According to $B_1 \geq 0$, $B_2 < B_{2,min}$, $B_3 < B_{3,min}$, and $B_4 < B_{4,min}$, we can get the fog computing total bandwidth B fits (36) or (37), in which $B_{3,min} = 0$.

Until now, the first step has been done. Eight sub-optimal problems have been solved and each one got a range of B. Next, we process to the second step. The bandwidth B offered by fog computing is divided into smaller ranges according to the range of B obtained in the first step. Then, we calculate the utility of the cases in each range, and identify the one with the highest utility as the optimal one.

For instance, the eight ranges of B are as follows: $B^1 \in [2, 5]$, $B^2 \in [3, 6]$, $B^3 \in [2, 7]$, $B^4 \in [6, 9]$, $B^5 \in [5, 6]$, $B^6 \in [3, 7]$, and $B^8 \in [7, \infty)$. Then, the total bandwidth B can be divided in smaller range as $R^1 \in [2, 3]$, $R^2 \in [3, 5]$, $R^3 \in [5, 6]$, $R^4 \in [6, 7]$, $R^5 \in [7, 9]$, and $R^6 \in [9, \infty)$. B^1, B^3 and B^6 fall in to the range A^1. Using the utility functions in 1), 3) and 6), the sub-optimal utility is calculated using the beginning value respectively. For instance, $U^1 = 2.4$, $U^3 = 5.8$, $U^6 = 3$ Then, a conclusion can be drawn that the utility function in 3) is the optimal one in range A^1. Periodically, the optimal utility function is gotten in each range. Eventually, the optimal utility model is achieved by organizing them together in the given range of B.

V. NUMERICAL SIMULATIONS

In this section, a specific fog computing platform is considered. Based on its environment, the utility function is modeled. In the platform, the parameters are as follows. We assume that the four kinds of services have the same importance, so the utility weight factor α_i is set to be 1/4 for $i = 1, 2, 3,$ *or* 4. Considering each service, the utility of a unit function also has the same value, so the U_i is set to be 1 for $i = 1, 2, 3,$ *or* 4. The available bandwidth is B MB. The turning points of IES, HRTS and SRTS are $B_{2,min} = 1$ MB, $B_{3,min} = 2$ MB, and $B_{4,min} = 4$ MB.

Using the method shown in step 1 of section 4, the obtained ranges of B are $B^1 \in [13, \infty)$, $B^2 \in [6.7, 7]$, $B^{2'} \in [6.7, \infty)$, $B^3 \in [11, \infty)$, $B^4 \in [4.7, 5]$, $B^{4'} \in [4.7, \infty)$, $B^5 \in [9, \infty)$, $B^6 \in [5, 6]$, $B^{6'} \in [5, \infty)$, $B^7 \in [7, \infty)$, $B^8 \in [3, 4]$, and $B^{8'} \in [3, \infty)$. *i*) means in the *i*' th sub-optimal case. The outcome is shown in Figure 3.

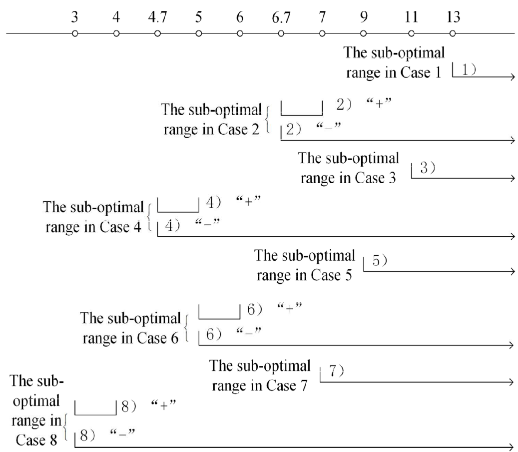

FIGURE 3. Sub-optimal utility ranges.

The total available bandwidth B can be in one of the ranges shown in Figure 4 which are $R^1 \in [3, 4]$, $R^2 \in [4, 4.7]$, $R^3 \in [4.7, 5]$, $R^4 \in [5, 6]$, $R^5 \in [6, 6.7]$, $R^6 \in [6.7, 7]$, $R^7 \in [7, 9]$, $R^8 \in [9, 11]$, $R^9 \in [11, 13]$, and $R^{10} \in [13, \infty)$. Next, the analysis is taken in every range.

1) If B falls into the range R^1, there are two sub-optimal cases which are 8)+ and 8)−. The utilities are calculated using the corresponding utility function respectively. Comparing the two utilities, we find that 8)− is bigger. So, 8) is the optimal case and the utility function is (39).

2) If B falls into the range R^2, there is only one sub-optimal case. The sub-optimal case turns to an optimal one and the utility function is (39).

3) If B falls into the range R^3, there are two sub-optimal cases which are 4)+ and 8)−. The utilities are calculated using the corresponding utility function respectively. Comparing the two utilities, we find that 8)− is bigger. So, 8) is the optimal case and the utility function also is (39).

4) If B falls into the range R^4, there are five sub-optimal cases which are 4)−, 6)+, 6)− and 8)−. The utilities are calculated using the corresponding utility function respectively.

Comparing the five utilities, we find that 6)− is the biggest. So, 8) is the optimal case and the utility function also is (31).

Using the same method, the optimal cases of R^5, R^6, R^7, R^8, R^9, and R^{10} are 6)−, 6)−, 6)−, 5), 5), and 1). The corresponding utility functions are (31), (31), (31), (25), (25) and (8).

The outcome is shown in Figure 4 in black rectangle.

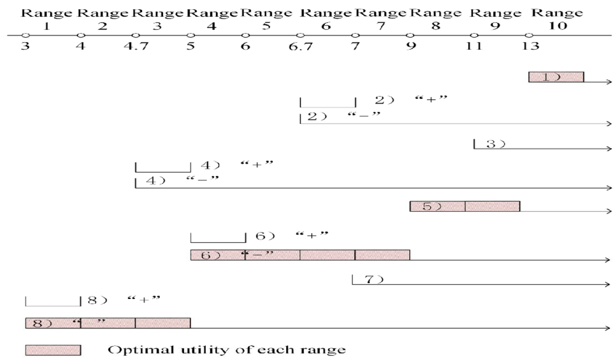

FIGURE 4. **Optimal utility ranges.**

Lastly, the optimal utility function is gotten as

$$U = \begin{cases} \phi_1 \quad 3 < B < 5, & B_1 = 1/\chi_1 - 1, B_2 = 0, \\ & B_3 = 0, B_4 = 4\chi_1 \\ \phi_2 \quad 5 \le B < 9, & B_1 = 1/\chi_2 - 1, B_2 = 0 \\ & B_3 = 0, B_4 = 4\chi_2 \\ \phi_3 \quad 9 \le B < 13, & B_1 = \chi_3 - 1, B_2 = 0 \\ & B_3 = 0, B_4 = \chi_3 \\ \phi_4 \quad B \ge 13, & B_1 = \chi_4 - 1, B_2 = \chi_2 \\ & B_3 = 2, B_4 = \chi_2. \end{cases} \tag{40}$$

$\phi_1 = 0.25(\log(B_1+1) + B_4^2/8)$, $\phi_2 = 0.25(4\phi_1 + 1)$, $\phi_3 = 0.25(\log(B_1+1) + \log B_4 + \log B_2 + 1)$, $\phi_4 = 0.25(\log(B_1+1) + \log B_2 + \log B_4 + 1)$; $\chi_1 = ((B+1)/8) - \sqrt{((B+1)/8)^2 - 1/4}$, $\chi_2 = ((B-1)/8) - \sqrt{((B-1)/8)^2 - 1/4}$, $\chi_3 = (B-1)/2$, $\chi_4 = (B-1)/3$.

The outcome of (40) is drawn in Figure 5. Rrawing up the following conclusions is possible. Firstly, if the bandwidth is optimally allocated, the network survivability is prolonged. The reason is that users need less time to complete the services. Secondly, the utility of mobile fog computing enhances with the increase of total available bandwidth. Thirdly, there are some singular points which cut the utility line into different ranges. This feature implies that the increase of the available bandwidth, at some points, can dramatically raise the utility, since the serving model is changed.

Besides, in Figure 5, we compared our proposed scheme with the averaged scheme. In this last, the available bandwidth is equally divided into four kinds of services. Then, the utility can be calculated. Considering Figure 5, it is possible to note that the proposed scheme works better than the average one. As a consequence, the fog computing network can get more utility by using the solution proposed in this work.

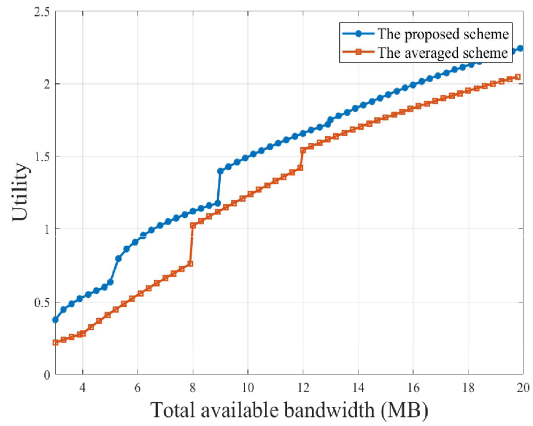

FIGURE 5. **Utilities with different schemes.**

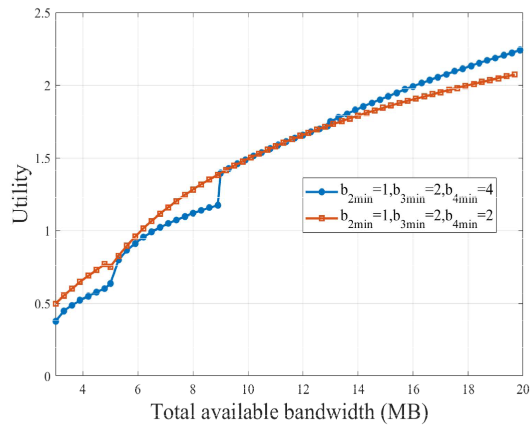

FIGURE 6. **Utilities with different threshold value of SRTS.**

Subsequently, we set $B_{4,min} = 2$, while the values of other parameters are unchanged. Again, we calculate the optimal utility and compare it with $B_{4,min} = 2$. The outcome is shown in Figure 6, and we can get that under different parameters, the optimal utility is different. In order to get the optimal utility function in actual situation, the values of the parameters should be determined firstly.

Afterward, the following scenario is considered. The second kind of services (IES) is more important than the other three, and the corresponding utility weight is changed from $1/4$ to $1/2$, and the other three utility weights are all $1/6$. The values of other parameters are unchanged. Even in this case, we calculate the optimal utility. Figure 7 shows the outcome that allows understanding of the increase of the utility along with the increase of total available bandwidth. It is useful to note that comparing the two optimal utilities, in some parts, the scheme with $\alpha_2 = 0.25$ is better than the other one with $\alpha_2 = 0.5$, while in other sectors, opposite conclusion is derived. The reason behind is due to environmental difference. Therefore, the optimal utilities are different.

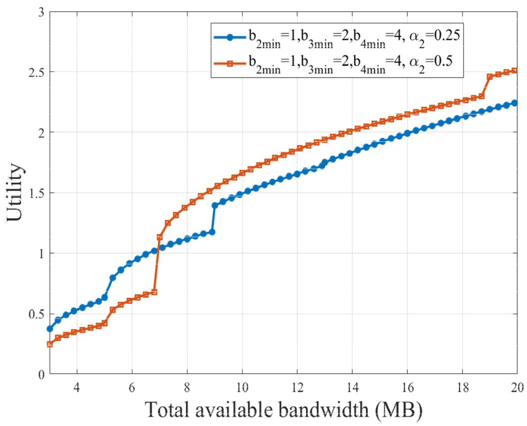

FIGURE 7. Utilities with different utility weight factor value of IES.

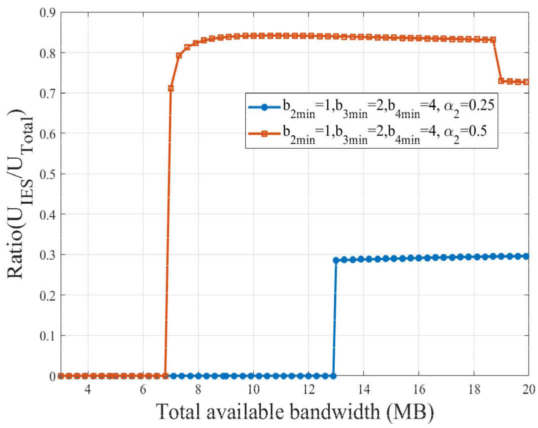

FIGURE 8. Ratios between U_{IES} and U_{Total} with different utility weight factor value of IES.

Under the same scenario, we simulate the utility ratios between IES and the whole four kinds of services. The result is shown in Figure 8. It is possible to note that the ratio is the same while the total available bandwidth is smaller than 7. The reason is that IES does not get any bandwidth in the two optimal scheme while the total available bandwidth is smaller than 7. Consequently, the ratio with $\alpha_2 = 0.5$ is larger than $\alpha_2 = 0.25$. This situation implies that the IES can get more share based on the assumption.

VI. CONCLUSIONS

Vehicular fog computing aims to accelerate the service acquisition, to save more additional energy, and to improve the survivability of the system. In this paper, the resource allocation issues related to vehicular fog computing have been analyzed. A serving model has been introduced based on three layers, i.e., the cloud layer, fog layer, and vehicular computing layer. In the proposed solution, the bandwidth allocation is processed between the fog layer and vehicular computing one. Moreover, the vehicular services are separated into four types (TES, IES, HRTS, and SRTS). By using the utility function, the proposed model has been developed to describe the benefits of bandwidth allocation through these four kinds of services. Solving a mathematic model has been necessary, and, in the solution introduced in this work, the range of the available bandwidth has been partitioned into smaller portions. Furthermore, a sub-optimal principle has been presented. In each small portion, all the possible utilities are calculated with the aim to make the sub-optimal solution as an optimal one. Numerical simulations have been performed to demonstrate both the whole procedure of the scheme and the final optimal utility.

In conclusion, this paper has clearly shown what the correlation regarding the bandwidth allocation between fog computing layer and vehicular computing layer is. In the future, further considerations related to overall three layers should be given with the goal enhancing the functionality of the proposed model further.

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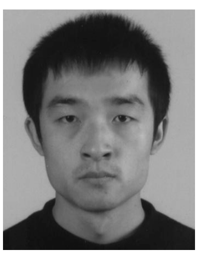

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