

Distributed Media Services in P2P-Based Vehicular Networks

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Abstract—A significant challenge in vehicular networks is to efficiently provide heterogeneous media services with the constraints of limited resources, high mobility, opportunistic contact, and service time requirements. In this paper, we study the heterogeneous media provision in peer-to-peer (P2P)-based vehicular networks and develop fully dynamic service schemes with the goals of maximizing the total user-satisfaction and achieving a certain amount of fairness. We first construct a general user-satisfaction model according to the network transmission mechanism, as well as different media delay-satisfaction characteristics. Then, we formulate the media service as an optimization problem and propose a joint content dissemination and cache update scheme. We also provide the exact steps to achieve the optimal solution at equilibrium, given the user-satisfaction function. Furthermore, we extend the proposed service scheme by addressing the fairness problem. Unlike prior works that target at bandwidth or demand fair, we propose a media-aware satisfaction-fairness strategy, which is aware of the characteristic of user-satisfaction and media content and ensures max-min satisfaction-fairness sharing among multiple vehicles. It is worth noting that both schemes are designed in a distributed manner, which is amenable to online implementation for vehicle networks. In addition, we provide extensive simulation results that demonstrate the effectiveness of our proposed schemes.

Index Terms—Fairness, multimedia service, peer-to-peer (P2P), quality of service (QoS), vehicular networks.

I. INTRODUCTION

VEHICULAR ad hoc networks are considered to be one of the most promising techniques for providing road safety and innovative mobile applications [1]–[10]. With the proliferation of the distributed peer-to-peer (P2P) cooperative transmission technologies, P2P-based vehicular networks have recently received a substantial amount of interest [1], [2], [4], [6]. It has been shown that one can significantly increase the

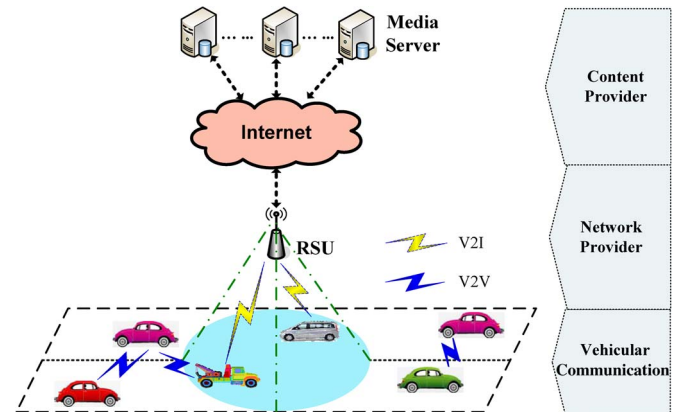


Fig. 1. System architecture of heterogeneous media services for vehicular networks.

capacity of ad hoc networks by sharing contents in each vehicle [2], [4]. Therefore, such P2P-based vehicular networks make it possible to provide large data heterogeneous media content for moving vehicles [2], [5], [6], [8]. Media service over vehicular networks is a very interesting topic as it can greatly bring benefit to our daily life [2], [3], [5]. For instance, highway hazard and traffic jam messages can be used to improve traffic safety and efficiency, and entertainment services such as MP3 music and video news can also be provided to the users in moving vehicles.

Fig. 1 shows a typical heterogeneous media-service architecture for vehicular networks, which contains three parts, namely, a vehicular internetwork, a network provider, and a content provider [10]. In the vehicular communications part, a vehicle accesses the roadside units (RSUs) via direct vehicle-to-infrastructure communications when the vehicle enters into the coverage of the RSU or via multihop vehicle-to-vehicle (V2V) communications when the vehicle is out of the RSU's coverage. In the network provider part, RSUs act as Internet gateways to link vehicles and media-service providers. The media servers in the content provider part possess different media-service databases. With regard to P2P-based service fashion, all vehicles themselves request media services and help provide media services to others when they meet each other and are within the V2V transmission range.

Generally speaking, the problem of heterogeneous media services over P2P-based vehicular networks is, as compared with traditional content delivery or data dissemination, further complicated by the network environments and application contents, including the following: 1) *Content dissemination*: How do we distribute different media content to adapt dynamic

Manuscript received May 19, 2010; revised August 20, 2010 and October 26, 2010; accepted December 3, 2010. Date of publication December 30, 2010; date of current version February 18, 2011. This work was supported in part by the Alexander von Humboldt Foundation, by the Science Technology Project of the Ministry of Transport of the People's Republic of China under Project 2009-353-332-290, and by the AURORA project of the Research Council of Norway under Project 205048/V11. The review of this paper was coordinated by Dr. L. Cai.

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Digital Object Identifier 10.1109/TVT.2010.2102782

vehicular networks and achieve optimal user-satisfaction? 2) *Cache update*: How do we update each vehicle's cache in the context of mobile opportunistic meet environment?¹ 3) *Fairness*: How do we provide satisfaction-centric fairness for multivehicle streaming multiple services concurrently? These three problems interact with each other and, thus, form a challenging user-centric network service problem across the heterogeneous services, dynamic networks, and multiple vehicles.

In this paper, our objective is to propose a distributed heterogeneous media-service scheme for P2P-based vehicular networks to maximize the total user-satisfaction and achieve a certain amount of fairness. We first identify an objective function that incorporates the media characteristics and user-satisfaction and then explore how to construct a stable, distributed, dynamic, and fair system that optimizes this objective. Although some data-dissemination protocols can be obtained by extending current algorithms [11]–[13] that are known to achieve the maximum system capacity for P2P networks, these works ignore the media content or mobile opportunistic environment. Consequently, these solutions may not be optimal for this work. It is important to emphasize that compared with general data dissemination, media services in vehicular networks are characterized by *media content* and *service time*. Different media contents correspond to different user-satisfaction functions. Service time, which is defined as the elapsed time between the service demand and its fulfillment, cannot be neglected in vehicular networks.

In contrast to the abundance of literature studying general data dissemination [1], [6], [8], there are only a few methods that have been proposed for media services over vehicular networks. Reference [3] proposes location-aware services over vehicular ad hoc networks; however, they do not take into account the differences among the multiple services [5] and [9] provide wireless media transmission schemes for vehicular networks, but vehicle opportunistic meet and service time are not considered. Up to now, the problem of heterogeneous media services for vehicular networks still remains a challenging issue, which motivates the present study. The fundamental contributions of this paper are twofold.

- 1) We provide a novel *distributed heterogeneous media-service scheme* in the context of P2P-based vehicular networks. Since this is a classic mobile opportunistic environment, it is difficult to gather global information of the available media services for each vehicle. Therefore, one requires appropriate joint *content dissemination and cache update* (CDCU) using as little feedback as possible. Different from previous works on media services for wireless networks [10]–[12] in which user satisfaction is not a concern, we consider the impact of user satisfaction on practical media dissemination. Specifically, we propose a general model in terms of service time and user-satisfaction to capture this impact. Moreover, unlike conventional popularity-aware media-service schemes [2], [13], [14], we study the behavior of cache update that knows neither the current popularity of the media services nor the cache allocation.

- 2) We extend the media-service scheme by *proposing a strategy of media-aware satisfaction–fairness* (MASF), which is aware of the characteristics of media content and ensures max–min satisfaction–fairness. References [15]–[18] employ an explicit utility function of the rate, but they are not specifically designed for media services. In addition, the distributed algorithms in [15], [16], and [18] may need a lot of computational complexity, and the service time may increase dramatically such that user-satisfaction may be poor. Different from [15] and [18], we assume no explicit utility function or mapping rule, but instead, we use a media-service counter (MSC) that can be easily and explicitly calculated (see Section III). Furthermore, our work is also different from [19]–[21], which manage resources with the granularity of traffic classes or the packets importance based on the distortion and decoding dependence.

The rest of this paper is organized as follows: Section II describes the heterogeneous media-service model for vehicular networks. In Section III, we propose a distributed heterogeneous media-service scheme to maximize the total user-satisfaction by jointly considering CDCU. We extend the media-service scheme by addressing the fairness problem and provide an MASF strategy in Section IV. Then, extensive simulation results and comparisons are provided in Section V. Section VI concludes this paper and points to future work.

II. SYSTEM MODEL AND DESCRIPTION

A. Vehicle Meet

Consider a vehicular network of $\mathcal{V} = \{1, 2, \dots, i, \dots\}$ vehicles (users) and $\mathcal{M} = \{1, 2, \dots, m, \dots\}$ media services. $|\mathcal{V}|$ and $|\mathcal{M}|$ represent the numbers of vehicles and media services, respectively. For media service m and vehicle i , we define $X_{m,i} = 1$ if vehicle i is in possession of service m , and $X_{m,i} = 0$ otherwise. The matrix $\mathcal{X} = (X_{m,i})_{m \in \mathcal{M}, i \in \mathcal{V}}$ represents the states of the distributed cache of the whole system.

We denote the total number of services m in the system by $X_m = \sum_{i \in \mathcal{V}} X_{m,i}$. In addition, we assume that all vehicles have the same cache size c . It should be noted that this is not a critical assumption, and most of the following results can be trivially extended to different cache sizes. Hence, media content allocation \mathcal{X} should satisfy the constraint of the cache size, i.e.,

$$\sum_{m \in \mathcal{M}} X_{m,i} \leq c \quad \forall i \in \mathcal{V}. \quad (1)$$

Vehicles may meet with each other in an opportunistic way, and this provides the opportunity for media services. Suppose that meets between every couple of vehicles follow independent and memoryless processes. This helps us find the optimal scheme before evaluating them using real traces for this complex system [24]. We assume that vehicle i meets vehicle j according to a Poisson process with rate $\mu_{i,j}$. Specifically, if each vehicle meets with others with the same probability, namely, $\mu_{i,j} = \mu$ for all vehicles, we call this as a *homogeneous meeting* model; on the contrary, a *heterogeneous meeting* model is a situation where the meet between any vehicle is independent of each other.

¹ Every vehicle has a memory cache to store different media contents.

Note that a homogeneous meeting model is not an exceptional assumption: 1) This model is widely used in data dissemination in the context of vehicular networks for the sake of analysis convenience [6], [22], [23], [25]; 2) a vehicle itself cannot know the probability of the vehicle it meets without the help of a center controller; 3) a vehicular network is a dynamic system, where vehicle meets may change dramatically within a short period; 4) the homogeneous meeting model is relaxed in the numerical results, and it can be used in a heterogeneous meeting model when each $\mu_{i,j}$ is available; this will be validated by simulation results in Section V.

B. Media Service

Each media content stored in vehicle i ($i \in \mathcal{V}$) has a time-stamp, indicating when it is originally downloaded from an RSU. $T_{m,i}(t)$ is the time stamp of user i 's media content m ($m \in \mathcal{M}$) at time t . Vehicle i will copy vehicle j 's media content m if they satisfy the V2V communication, and the content stored at j is newer than that of i , i.e., $T_{m,i} < T_{m,j}$. Then, both of their time stamps become $\max\{T_{m,i}, T_{m,j}\}$ after their communication. In addition to the media-service content, we are also interested in the age $A_{m,i}$ of the media m stored in each vehicle i 's cache, and it can be defined as [11]

$$A_{m,i}(t) = T - T_{m,i}(t), \quad m \in \mathcal{M}; \quad i \in \mathcal{V} \quad (2)$$

where T is the current time. In particular, $A_m = \sum_i A_{m,i}$ denotes the average age of m in the vehicular networks.

Vehicles demand for media services in the form of requests. The process of demand for different services has different rates, reflecting heterogeneous media contents. We denote the total rate of demand for media service m by R_m and the probability of demand at vehicle i by $\rho_{m,i}$. Hence, vehicle i makes a new request for service m with rate $R_m \rho_{m,i}$. The probability $\rho_{m,i}$ can capture different popularity profiles in different vehicle populations. Without loss of generality, media services can be sorted according to the demand in decreasing order (i.e., $R_m \geq R_n$ for $m \leq n$). To depict the real vehicular network environment, we assume that the distribution of the service demand follows the *Pareto* model $R_m \propto m^{-\omega}$ ($\omega > 0$) for all $m \in \mathcal{M}$.

Since vehicles may demand heterogeneous media services, we need a flexible model to account for their satisfactions. As previously stated, media service over vehicular networks is greatly impacted by service time. Let $h_m(t)$ be the satisfaction function for media service m , which represents the degree of satisfaction for the service time t . Since users always prefer to fulfill the service demand as soon as possible, $h_m(t)$ should be a nonincreasing function of t . In the following, we present several typical satisfaction functions.

- 1) *Threshold function*: $h_m(t) = \mathbf{1}_{t \leq \tau}$. This function corresponds to delay-sensitive media services such as live videos. If the service time t is larger than a given tolerate threshold τ , the user will give up this service request.
- 2) *Try-best function*: $h_m(t) = \exp(-\tau t)$. In this case, media services can be fulfilled at any time, although the sooner the better (e.g., music entertainment).

- 3) *Reward function*: $h_m(t) = t^{1-\tau}/(\tau - 1)$, $1 < \tau \leq 2$. This satisfaction function corresponds to critical emergency media services, e.g., road hazard messages and highway information, which vary very quickly. In this case, a large reward is provided for a prompt demand fulfillment.

In addition, we assume that each vehicle can transmit the media contents instantly. For small files, this assumption is reasonable. If the vehicles transmit extremely large files, we can divide a large file (particularly for some documents) into many small pieces, which are convenient for transmission.

III. DISTRIBUTED MEDIA-SERVICE SCHEME

We define $G_{m,i}(\mathcal{X})$ to be the expected gain generated by a request for service m from vehicle i . Hence, we seek to optimize *total user-satisfaction* $G(\mathcal{X})$ in terms of all the vehicles, i.e.,

$$\begin{aligned} \max \quad & G(\mathcal{X}) = \sum_{m \in \mathcal{M}} \sum_{i \in \mathcal{V}} R_m \rho_{m,i} G_{m,i}(\mathcal{X}) \\ \text{s.t.} \quad & \sum_{m \in \mathcal{M}} X_{m,i} \leq c \\ & X_{m,i} \in \{0, 1\} \quad \forall i \in \mathcal{V} \quad \forall m \in \mathcal{M}. \end{aligned} \quad (3)$$

The total user-satisfaction is affected by the gain perceived by users, the popularity of media service, as well as the cache allocation. As a consequence, this media-service problem is coupled with media content allocation, media-service strategy, and vehicle cache update. In the remaining of this section, we propose a distributed media-service scheme where each vehicle and media service jointly solves this problem through efficient cooperation.

A. CDCU

We denote function $h'_m(t)$ as the first-order differential satisfaction function h_m under a continuous-time meeting model, i.e.,

$$h'_m(t) = \frac{dh_m(t)}{dt}. \quad (4)$$

The value of $h'_m(t)$ is always negative as $h_m(t)$ is a nonincreasing function (see Section II-B). $h'_m(t)$ can be interpreted as "gain sensitivity" over service time (i.e., the amount of decrease in gain is incurred per unit increase in service time). Note that when $h_m(t)$ is not derivable (e.g., the threshold function), $h'_m(t)$ is not defined as a function but as the distribution. The second row of Table I shows the expression of $h'_m(t)$ for the previously introduced satisfaction functions.

Lemma 1: For the given Poisson vehicle meeting model, $G_{m,i}(\mathcal{X})$ can be expressed as

$$h_m(0^+) - (1 - X_{m,j}) \int_0^\infty \exp\left(-t \sum_{i \in \mathcal{V}} X_{m,i} \mu_{i,j}\right) h'_m(t) dt \quad (5)$$

where $j \in \mathcal{V}$, and $j \neq i$.

TABLE I
 DIFFERENT FUNCTION EXPRESSIONS UNDER DIFFERENT USER-SATISFACTION FUNCTIONS

| Model | Threshold function | Try-Best function | Reward Function |
|--|--|---|--|
| Satisfaction func. $h_m(t)$ | $\mathbf{1}_{t \leq \tau}$ | $\exp(-\tau t)$ | $\frac{t^{1-\tau}}{\tau-1} (1 < \tau \leq 2)$ |
| Diff. satis. func. $h'_m(t)$ | Dirac. at $t = \tau$ | density $t \mapsto -\tau \exp(-\tau t)$ | density $t \mapsto -t^{-\tau}$ |
| Total user-satis. func. $G(\mathcal{X})$ | $\sum_m R_m (1 - e^{-\mu\tau X_m})$ | $\sum_m R_m (1 - \frac{\tau}{\tau + \mu X_m})$ | $\sum_m R_m X_m^{\tau-1} \frac{\mu^{\tau-1} \Gamma(2-\tau)}{\tau-1}$ |
| Priority func. φ | $R_m \mathcal{M} \mu \tau e^{-\mu\tau X_m} / \mathcal{V} $ | $R_m \frac{\mu}{\tau} (\mathcal{M} + \mathcal{V} \frac{\mu}{\tau} X_m)^{-2}$ | $R_m (\mu \mathcal{M})^{\tau-1} (X_m \mathcal{V})^{2-\tau} \Gamma(2-\tau)$ |
| Popularity func. ϕ | $\frac{\mu\tau \mathcal{V} }{y \mathcal{M} } \exp\{-\frac{\mu\tau \mathcal{V} }{y \mathcal{M} }\}$ | $\left(1 + \frac{\tau y \mathcal{M} }{\mu \mathcal{V} } + \frac{\mu \mathcal{M} }{y \mathcal{V} \tau}\right)^{-1}$ | $(y \mathcal{M})^{1-\tau} (\mu \mathcal{V})^{\tau-1} \Gamma(2-\tau)$ |

Proof: Let Y be an exponential random variable with parameter λ . Then, for any derivable function f defined on $[0, \infty)$ which admits a limit in 0^+ , we have

$$\mathbb{E}[f(Y)] = f(0^+) + \int_0^\infty \exp(-\lambda t) f'(Y) dY \quad (6)$$

where $\mathbb{E}[\cdot]$ represents the expectation of a nonnegative random variable. According to the definition of expected gain, $G_{m,i}(\mathcal{X}) = \mathbb{E}[h_m(t)]$ (t is the service time). For our proposed model, when the user i can provide the demand service m , the time consumed before this request is an exponential random variable with parameter $\sum_{i \in \mathcal{V}} X_{m,i} \mu_{i,j}$. ■

In the case of the homogeneous vehicle meeting model, the general expression (5) can lead to a closed-form expression. Specifically, the expression only depends on $(X_{m,i})_{m \in \mathcal{M}, i \in \mathcal{V}}$ and the number of services $(X_m)_{m \in \mathcal{M}}$. Similarly, if all $|\mathcal{V}|$ vehicles provide the same number of media services (i.e., $\rho_{m,i} = 1/|\mathcal{V}|$), the total user-satisfaction is given by

$$G(\mathcal{X}) = \sum_{m \in \mathcal{M}} R_m \left(h_m(0^+) - \left(1 - \frac{X_m}{|\mathcal{V}|}\right) \times \int_0^\infty e^{-t\mu X_m} h'_m(t) dt \right). \quad (7)$$

Note that $G(\mathcal{X})$ is a concave function of X_m ($m \in \mathcal{M}$) for the homogeneous meeting. According to [26, Th. 3.4–3.7], the relaxed total user-satisfaction can be found by using a gradient descent algorithm. Here, the term “relaxed” means that X_m is allowed to take real values in the optimization operation. Furthermore, (7) can also be extended to the heterogeneous meeting model, and the corresponding characteristics then remain the same [26, Th. 4.2–4.3].

To get the optimal total user-satisfaction, we propose the joint CDCU scheme. A very important issue for the dynamic vehicular networks is that CDCU implicitly adapts to current dissemination, cache update, and the collection of requests without the explicit estimators or feedback of the media-service popularity or current cache allocation. Specifically, each vehicle keeps an MSC for each new request instead of estimating the popularity of each service as in [2] and [13]. Whenever a request is fulfilled, the final value of the corresponding counter is proportional to the service popularity, which is used to calculate the number of new dissemination activities of that service. Since each vehicle’s cache is limited, the new injected media content must take place of older media contents; we also use

 TABLE II
 CDCU SCHEME

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01: Input:
02: Initial MSC value of media service  $m$  in vehicle  $i$  is  $MSC_{m,i} = 0$ ;
03: Popularity function  $\phi$  and priority function  $\varphi$ ;
04: Output:
05: Optimal Joint Content Dissemination and Cache Update Scheme;
06: Procedure CDCU
07: if (vehicle  $i$  begins requesting media service  $m$ )
08:   if (vehicle  $i$  meets vehicle  $j$ )
09:     if (vehicle  $j$  can not provide service  $m$ )
10:        $MSC_{m,i} = MSC_{m,i} + 1$ ;
11:     else
12:       Vehicle  $i$  copy media content  $m$  for vehicle  $j$ ;
13:       The popularity function of  $m$  is set  $\phi(MSC_{m,i}) \geq 1$ ;
14:       The priority of  $m$  in vehicle  $i$ ’s cache is set  $\varphi(MSC_{m,i})$ ;
15:        $m$  replaces the minimum priority media in  $i$ ;
16:       if ( $\phi(MSC_{m,i}) \geq 0$ )
17:          $i$  transmits forwardly  $m$  to  $j$ ’ it meets from then on;
18:          $m$  replaces the minimum priority media in  $j$ ’;
19:          $\phi(MSC_{m,i}) = \phi(MSC_{m,i}) - 1$ ;
20:       endif
21:       if ( $j$ ’ has the media  $m$ )
22:          $m$  will be reserved in both vehicles;
23:          $MSC_{m,i} = MSC_{m,i} - 1$ ;
24:       endif
25:     endif
26:   endif
27: endif
    
```

MSC and “freshness” to set the priority for each media content. The implementation steps of CDCU are shown in Table II. Note that the popularity and priority functions are very important, and we will describe the mechanisms to set them, given the knowledge of the satisfaction function in Section III-B.

To make the proposed CDCU scheme work smoothly in vehicular networks, the following rules are necessary: 1) For each media service, it can be only served for one vehicle at the same time; and 2) since each vehicle’s cache is randomly replaced, when a media service needs to be provided, this media content cannot be replaced in the server until it is fulfilled.

B. Popularity and Priority Functions

According to the boundary and rounding effects [26], it is difficult to derive a closed-form expression for maximizing the total user satisfaction if X_m ($m \in \mathcal{M}$) only takes integer values. However, when the number of media services $|\mathcal{M}|$ becomes very large, X_m may take a larger value (this is particularly true for popular media services). In this case, the difference between the optimal solution and the relaxed optimization (where X_m may take real values) is proportional to $1/|\mathcal{M}|$ [26]. Here, we use this rule to find a simple equilibrium condition for the given relaxed optimization problem.

Since the objective function (3) is a classic multivariate optimization problem, it is difficult to take the derivative of $G(\mathcal{X})$ with respect to \mathcal{X} directly. To get around the difficulty, motivated by [27], we take the logarithm operator on $G(\mathcal{X})$ to get $G(\tilde{\mathcal{X}})$. Since the variant relativity can be reduced by this logarithm operator, we can decompose $G(\tilde{\mathcal{X}})$ using the subfunction summation method [27]. For any $\tilde{\mathcal{X}} = \lg \mathcal{X} = \lg(X_m)_{m \in \mathcal{M}}$, we denote by $(\Delta G / \Delta \tilde{X}_m)(\tilde{\mathcal{X}})$ the *unit increment* obtained when a media service m is provided. It can be defined as

$$\frac{\Delta G}{\Delta \tilde{X}_m}(\tilde{\mathcal{X}}) = G(\lg(X_1, \dots, X_{m-1}, X_{m+1}, \dots, X_{|\mathcal{M}|})) - G(\lg \mathcal{X}). \quad (8)$$

For a given m , the unit increment $(\Delta G / \Delta \tilde{X}_m)(\tilde{\mathcal{X}})$ is independent from \tilde{X}_n for $n \neq m$. Note that this is intuitive, as for a fixed service number of a given media, the service time of this media service is independent from other services. In other words, we may get $(\Delta G / \Delta \tilde{X}_m)(\tilde{\mathcal{X}}) = G'_m(\tilde{X}_m)$, where

$$G'_m(\tilde{x}) = R_m \left(1 - \frac{\tilde{x}}{|\mathcal{V}|}\right) \int_0^\infty (1 - e^{-\mu t \tilde{x}}) h'_m(t) dt. \quad (9)$$

Therefore, the value of the total user satisfaction can be decomposed for each media service m , i.e.,

$$G(\tilde{\mathcal{X}}) = \sum_{m \in \mathcal{M}} G'_m(\tilde{X}_m). \quad (10)$$

Since the function $G(\tilde{\mathcal{X}})$ is concave, the functions G'_m ($m \in \mathcal{M}$) in (10) are all nonincreasing. As to our CDCU scheme, G'_m can be viewed as the integration of the popularity function ϕ and the priority function φ . According to the aforementioned G'_m characteristics, we can get the following theorems on ϕ and φ .

Theorem 1: (Expression of the Priority Function): Letting X be the solution of the relaxed total user-satisfaction maximization and $\tilde{X} = \lg X$, we have

$$\frac{R_m}{A_m} \varphi(\tilde{X}_m) = \frac{R_n}{A_n} \varphi(\tilde{X}_n) \quad \forall m, n \in \mathcal{M} \quad (11)$$

where we define φ as

$$\tilde{X} \mapsto \int_0^\infty \frac{\sum_m h'_m(t)}{|\mathcal{M}|} \frac{\sum_m A_m(t)}{|\mathcal{M}|} \mu t e^{-\mu t \tilde{X}} dt. \quad (12)$$

Proof: See Appendix A. ■

We now describe the relationship between the priority function and the popularity function. We first observe that the expected value of MSC for service m is proportional to $1/X_m$, since whenever a vehicle meets others, there is roughly a probability $X_m/|\mathcal{V}|$ that the media service m can be provided. Hence, we can set the priority function $\phi(|\mathcal{V}|/X_m)$ as a first order of X_m . In addition, for each vehicle cache, a new media content replaces m with probability $X_m/c|\mathcal{V}|$. Moreover, the media-service ability is inversely proportional to the number of media

services $|\mathcal{M}|$ for all the services. Therefore, the service number of each media m follows the set of differential equations, i.e.,

$$\frac{dX_m}{dt} = \frac{R_m}{|\mathcal{M}|} \phi\left(\frac{|\mathcal{V}|}{X_m}\right) - \frac{X_m |\mathcal{M}|}{c|\mathcal{V}|} \sum_{n \in \mathcal{M}} \frac{R_n}{|\mathcal{M}|} \phi\left(\frac{|\mathcal{V}|}{X_n}\right). \quad (13)$$

In a stable steady state, the creation of new services is equal to the deleted or replaced services. Hence, we have

$$R_m \cdot \frac{c|\mathcal{V}|}{X_m |\mathcal{M}|} \phi\left(\frac{|\mathcal{V}|}{X_m}\right) = \sum_{n \in \mathcal{M}} \frac{R_n |\mathcal{V}|}{X_n} \phi\left(\frac{|\mathcal{V}|}{X_n}\right). \quad (14)$$

The right-hand side of (14) is a constant, and therefore, we can write

$$\frac{R_m}{X_m} \phi\left(\frac{|\mathcal{V}|}{X_m}\right) = \frac{R_n}{X_n} \phi\left(\frac{|\mathcal{V}|}{X_n}\right) \quad \forall m, n \in \mathcal{M}. \quad (15)$$

Alternatively, the steady state of this scheme satisfies the equilibrium condition of Theorem 1 if and only if we have

$$\varphi(x) = \frac{|\mathcal{M}|}{cx} \phi\left(\frac{|\mathcal{V}|}{x}\right) \quad \forall x > 0 \quad (16)$$

where ϕ was defined in Theorem 1. Therefore, it is easy to get the following lemma.

Lemma 2: (Relationship Between the Priority Function and the Popularity Function): Given the MSC y , the system achieves the maximum total user satisfaction when the popularity function $\phi(y)$ and the priority function $\varphi(y)$ satisfy

$$\phi(y) = \frac{c|\mathcal{V}|}{y|\mathcal{M}|} \varphi\left(\frac{|\mathcal{V}|}{y}\right) \quad \forall y > 0. \quad (17)$$

Therefore, we can derive the following theorem.

Theorem 2: (Expression of the Popularity Function): The steady state of CDCU satisfies the equilibrium condition if and only if

$$\phi(y) \propto \frac{c|\mathcal{V}|}{y|\mathcal{M}|} \int_0^\infty \mu t e^{-\mu t \frac{c|\mathcal{V}|}{y|\mathcal{M}|}} h'_m(t) dt. \quad (18)$$

Outline of the Proof: The basic idea to prove the steady state is to decouple the coupled ϕ (coupled with $|\mathcal{M}|$ and $|\mathcal{V}|$) by introducing an auxiliary variable and an additional constraint and then use a Lagrange dual decomposition to decouple the constraints. The core proof procedure is similar to the proof in [28, Th. 3]. ■

Proposition 1: The optimal value of X_m , $m \in \mathcal{M}$, can be found by a greedy algorithm, which uses at most $O(|\mathcal{M}| + c \lg(|\mathcal{M}||\mathcal{V}|))$ steps.

Proof: See Appendix B. ■

Theorems 1 and 2 indicate that the priority and popularity functions of each media service can be set distributively to achieve the optimal and stable solution of the CDCU scheme. It is worth pointing out that the satisfaction function for each media service can be predefined in the practical implementation of CDCU. The fifth and sixth rows of Table I summarize the expressions of the different priority and popularity functions for the different user-satisfaction functions.

IV. MEDIA-AWARE SATISFACTION–FAIRNESS

We first consider the following scenario. Some media services are very popular (e.g., highway condition and parking information), whereas some media services receive low attention (e.g., restaurant messages). We can envision that the popular services have high user-satisfaction by using CDCU. On the other hand, some users usually cannot get a satisfactory service for those low popular media (they are sometimes also very important). To avoid this scenario, the following questions arise.

Questions: How do we achieve a good tradeoff between user fairness and user satisfaction? How do we ensure that the proposed distributed fairness scheme achieves a steady state in the context of vehicular networks?

Here, we will answer the preceding questions.

A. Fairness Versus Satisfaction

We consider the tradeoff between short-term fairness and long-term satisfaction. Specifically, an MASF strategy is proposed to deal with this problem. Each vehicle sends message indicating the number of MSCs in its cache to the vehicles it meets. Then, vehicles cooperatively decide the optimal upper and lower thresholds of the MSC for each media service. In particular, the media services with MSCs smaller than the lower threshold will be set as the lower threshold, whereas those with MSCs larger than the upper threshold will be set as the upper threshold. The media-service strategy along with priority and popularity functions is the same as with the CDCU scheme. With an MASF strategy, the vehicles and media contents can cooperate in a distributed way such that both service fairness and total user satisfaction are achieved among vehicles. For the case of multiple vehicles sharing media services, each shared media service decides a common threshold, and until then, each vehicle can accept minimum service satisfaction caused by the competition. The same threshold of media services makes each vehicle experience a max–min fairness distortion.

The core point of the MASF strategy is to find the optimal threshold of each media's MSC; each media finds an equal level for the vehicles that are not marked by a "Flag." Vehicle i sets its upper threshold Thr_i^u and lower threshold Thr_i^l over any vehicle j that it meets. If j agrees with the thresholds (i.e., they have the same thresholds), vehicle j chooses to hold the "Flag." If j has different thresholds, i transmits its media content proactively to j , and the new common thresholds for i and j are $Thr_i^u = Thr_j^u = \min\{Thr_i^u, Thr_j^u\}$ and $Thr_i^l = Thr_j^l = \max\{Thr_i^l, Thr_j^l\}$, and vehicle j marks itself "Flag." Then, the iteration goes to another round. This way, each vehicle gets satisfaction as high and fairly as possible. The frequent vehicle meeting and media updating are minimized, achieving the max–min satisfaction fairness. The detailed operation of MASF is shown in Table III.

B. Properties of the MASF Scheme

Proposition 2: The addition operations in MASF are at most the number of different media-service thresholds for each vehicle, where the updates are counted for all the vehicles if the media services are fully elastic without any upper bound.

TABLE III
MASF STRATEGY

| |
|---|
| 01: Input: |
| 02: Any vehicle $i \in \mathcal{V}$ is set 'Flag=FALSE'; |
| 03: $Thr_i^u = \max MSC$ for i , $Thr_i^l = \min MSC$ for i ; $/*Thr_i^u$ and Thr_i^l are the upper and lower thresholds for $i*/$ |
| 04: The MSC of media m in vehicle i is $MSC_{m,i}$; |
| 05: Output: |
| 06: Optimal Media-Awareness Satisfaction-Fairness Strategy; |
| 07: Procedure ThresholdSet $/*Set optimal threshold for all vehicles*/$ |
| 08: if (vehicle $j \neq i$ 'Flag=FALSE') |
| 09: if ($Thr_i^u = Thr_j^u$ AND $Thr_i^l = Thr_j^l$) |
| 10: vehicle j is set 'Flag=TRUE'; |
| 11: else |
| 12: $Thr_i^u = Thr_j^u = \min\{Thr_i^u, Thr_j^u\}$; |
| 13: $Thr_i^l = Thr_j^l = \max\{Thr_i^l, Thr_j^l\}$; |
| 14: vehicle j is set 'Flag=TRUE'; |
| 15: endif |
| 16: else |
| 17: vehicle j is set 'Flag=TRUE'; |
| 18: endif |
| 19: Procedure MediaUpdate $/*media serve counter update*/$ |
| 20: if ($MSC_{m,i} > Thr_i^u$) |
| 21: $MSC_{m,i} = Thr_i^u$; |
| 22: endif |
| 23: if ($MSC_{m,i} < Thr_i^l$) |
| 24: $MSC_{m,i} = Thr_i^l$; |
| 25: else |
| 26: $MSC_{m,i} = MSC_{m,i}$; |
| 27: endif |
| 28: Procedure MediaService |
| 29: The same to the CDCU presented in Table II; |

Proof: At each threshold updating, there will be at least a vehicle whose current threshold will not change after one V2V communication, and such a vehicle's media services will be fully utilized if the media contents are fully elastic with no upper bound. ■

Next, we consider the performance difference. Let $\hat{\mathcal{X}}$ denote the solution of MASF, and let \mathcal{X} represent that of CDCU. Define the cost function $D(G(\mathcal{X}), G(\hat{\mathcal{X}}))$ as the difference when MASF is employed. Therefore, (3) can be rewritten as

$$G(\mathcal{X}) = G(\hat{\mathcal{X}}) + \sum_{m \in \mathcal{M}} D(G_m(\mathcal{X}), G_m(\hat{\mathcal{X}})). \quad (19)$$

From (19), each media service will keep updating its state information, unless the performance difference employing the proposed update threshold becomes small. Hence, with the proposed MASF strategy, let e_m denote the MSC difference between MASF and CDCU for media m . Let

$$G_m^{\text{diff}} = \max_{m \in \mathcal{M}} \left(\frac{R_m}{A_m} \varphi(e_m) + \frac{|\mathcal{M}|}{c|\mathcal{V}|} \phi(e_m) \right) \quad (20)$$

represent the total user satisfaction difference between MASF and CDCU.

Proposition 3: If G_m^{diff} satisfies the following condition:

$$G_m^{\text{diff}} \leq \sum_{m \in \mathcal{M}} D(G_m(\mathcal{X}), G_m(\hat{\mathcal{X}})) \quad (21)$$

for any media $m \in \mathcal{M}$, the proposed MASF strategy converges to a stable state.

Proof: The right-hand side of (21) can be derived as

$$\begin{aligned}
 \text{RHS} &\geq G(\mathcal{X}) - G(\hat{\mathcal{X}}) \\
 &\geq \sum_{m \in \mathcal{M}} (G'_m(1) + G'_m(2) + \dots + G'_m(e_m)) \\
 &\geq \sum_{m \in \mathcal{M}} G'_m(e_m) \\
 &\geq \max_{m \in \mathcal{M}} \left(\frac{R_m}{A_m} \varphi(e_m) + \frac{|\mathcal{M}|}{c|\mathcal{V}|} \phi(e_m) \right) \Rightarrow G_m^{\text{diff}}. \quad (22)
 \end{aligned}$$

The remaining proof then follows [29, Prop. 2] so that the strategy converges to a stable state. ■

Proposition 4: If the cost function $D(G(\mathcal{X}), G(\hat{\mathcal{X}}))$ is a concave function of $\hat{\mathcal{X}}$ and the proposed MASF strategy converges to a stable state, the total user-satisfaction difference between the proposed MASF and CDCU schemes is not larger than $\sum_{m \in \mathcal{M}} G_m^{\text{diff}}$.

Proof: As long as the cost function $D(G(\mathcal{X}), G(\hat{\mathcal{X}}))$ is a concave function of $\hat{\mathcal{X}}$, the additional user-satisfaction function is a concave function. $((R_m/A_m)\varphi(e_m) + (|\mathcal{M}|/c|\mathcal{V}|)\phi(e_m))$ in (20) does not change with $\hat{\mathcal{X}}$ in each iteration. Therefore, when the proposed MASF strategy converges to a stable state, the worst satisfaction reduction is $\sum_{m \in \mathcal{M}} G_m^{\text{diff}}$. ■

V. NUMERICAL RESULTS

Here, we evaluate the performance of the CDCU and MASF schemes using extensive simulation based on real traces. To reveal performance improvements, we compare them with two alternative algorithms.

- 1) *Direct dissemination algorithm (DDA):* This idea is motivated by a classic carry-and-forward method [1], in which a moving vehicle carries a packet until a new vehicle moves into its vicinity, and then, it forwards the packet. In addition, a predictable vehicle mobility (corresponding the vehicle meeting model for CDCU) in [1] is also employed by the DDA. We also apply the proposed service request strategy on the DDA.
- 2) *Content sharing algorithm (CSA):* This idea is derived from [2], in which a popularity-aware data replacement algorithm is proposed to ensure that the density of different services is proportional to their popularity in the system steady state. Additionally, we employ the vehicle meeting model proposed for CDCU for the CSA.

To make the comparisons fair, we apply the user-satisfaction functions proposed in this paper to the DDA and the CSA and employ our cache update method for the DDA and the content dissemination strategy for the CSA.

A. Simulation Setup

In our simulation setup, 150 vehicles with 50 media services move within a fixed region of 5 km × 5 km. Each vehicle has five media services and can initiate requests for its interested media services. The data sets are extracted from 3 h of data, and vehicles meet each other whenever they are less than 250 m apart. The transmission range of each RSU is set to 1 km.

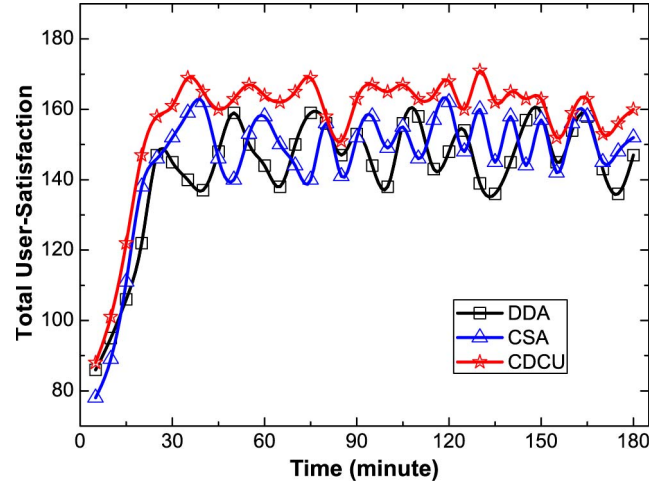


Fig. 2. Performance comparison when $\omega = 1$, $\mu = 0.03$, and threshold: try-best:reward = 1 : 1 : 1.

When vehicles enter into the RSU coverage, the RSU will broadcast five media services that are randomly chosen from the available 50 media servers, and the broadcast contents update every 10 min. Once the vehicles go out the coverage, they begin to demand the services they desire. If they cannot be served locally, these service demands will be sent to other encountered vehicles. Specifically, we tune the priority function φ and the popularity function ϕ according to Table I, which has been derived from the different satisfaction functions. We implemented the proposed scheme using an NS-2 simulator with the media access control layer parameters of IEEE 802.11p.

B. Simulation Results and Discussions

We first evaluate the performance of the CDCU scheme. Fig. 2 shows the total user-satisfaction along time. In this example, $\omega = 1$, $\mu = 0.03$, and the three kinds of user-satisfaction ratio are 1 : 1 : 1. The proposed CDCU scheme can be seen to achieve a higher performance than the other two schemes. In particular, the average total user satisfaction using the proposed CDCU scheme is 161.9, whereas it is 142.8 using the DDA and 145.9 for the case of the CSA. Thus, the proposed CDCU scheme can achieve almost 19.1 and 16.0 performance gains comparing with the DDA and CSA schemes, respectively. Fig. 2 also shows that the performance achieved by the CDCU scheme is sometimes closed to or worse than the performance of the alternative algorithms. That is because the CDCU scheme does not provide the service as soon as the demand is required, whereas it records the waiting time to fulfill the content dissemination. In Fig. 3, we repeat the results for different ω and μ values and user-satisfaction ratios, and similar observations can be held. Note that since each vehicle meets each other via an opportunistic method, their service satisfactions are dramatically varied over time. Moreover, at the beginning of this simulation, all of the vehicles have to pass the RSU to receive their original media services. However, each vehicle begins to demand the service from the beginning of the simulation, which leads to longer service time. Consequently, the proposed algorithm may take some time to converge to the average values.

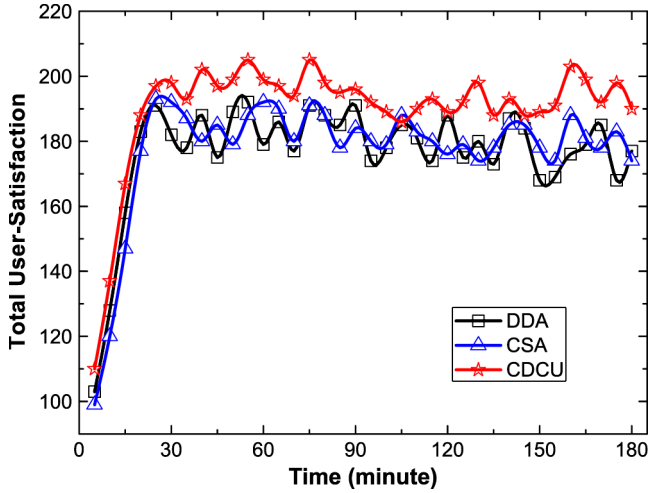


Fig. 3. Performance comparison when $\omega = 2$, $\mu = 0.05$, and threshold: try-best:reward = 1 : 2 : 1.

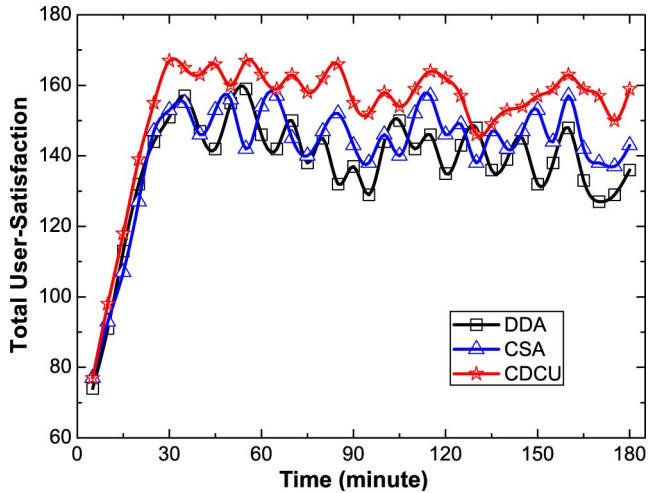


Fig. 4. Performance comparison under a heterogeneous meeting environment, $\mu \in [0.01, 0.1]$.

To evaluate CDCU in more practical vehicular networks, we relax the homogeneous meeting assumption. In particular, each meeting $\mu_{i,j}$ is a random variable that follows the Poisson distribution in $[0.01, 0.1]$. Fig. 4 shows the performance comparison of the previous three methods. It is observed that our proposal also has advantages over the competing algorithms. In addition, we test the proposed CDCU scheme in a dynamic environment where vehicles can join or leave the given network randomly, and the other settings are identical to those of Fig. 4. To avoid the case of unsatisfactory service due to the short stay in the vehicular networks, the vehicles join or leave the networks every 30 min. We employ two scenarios: Scenario-1 denotes $|\mathcal{V}| = 100$, $|\mathcal{M}| = 30$, and $c = 3$; and Scenario-2 represents $|\mathcal{V}| = 200$, $|\mathcal{M}| = 80$, and $c = 10$. Fig. 5 shows the performance results under different scenarios, which again demonstrate the efficiency of the proposed CDCU scheme. It is worth noting that our proposal can achieve a higher average performance in this dynamic environment; however, the performances in each time slot vary dramatically. This implies that the satisfaction–fairness property of CDCU is not good.

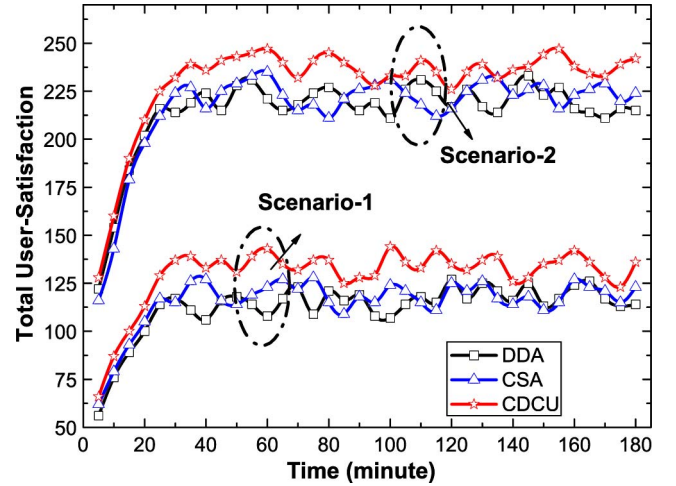


Fig. 5. Dynamic environment test (Scenario-1: $|\mathcal{V}| = 100$, $|\mathcal{M}| = 30$, and $c = 3$. Scenario-2: $|\mathcal{V}| = 200$, $|\mathcal{M}| = 80$, and $c = 10$).

Next, we evaluate the performance of MASF in terms of satisfaction–fairness in different scenarios. Note that Scenario-1 and Scenario-2 are identical to the settings of Fig. 5. We divide 180 min into six time slots, and each time slot lasts 30 min. To have a fair comparison, we introduce the fairness strategy presented in [4] for the DDA and the CSA. The comparison results are shown in Table IV. All the simulation results here have been obtained using 300 runs to obtain statistically average values. Based on the given objective simulation results, there are two main observations.

- 1) With regard to the average user-satisfaction value, MASF is comparable with that of CDCU and better than those of DDA and CSA schemes. For example, the differences between MASF and CDCU for each time slot in the two scenarios are only 0.7 and 0.6, respectively. Compared with DDA and CSA schemes, the proposed MASF scheme can achieve 15.6 and 12.7 performance improvements for Scenario-1 and 14.9 and 13.2 for Scenario-2. That is to say, MASF is derived from CDCU and holds the basic characteristics of CDCU.
- 2) With regard to fairness, MASF has the best performance. We can observe that although the CDCU scheme achieves the highest satisfaction, it results in unfairness in some cases. In addition, we consider the fairness of DDA and CSA schemes, and they can achieve a certain amount of improvement compared with the CDCU scheme. However, the media content is not considered, and their performances are lower than those of the proposed MASF scheme.

Finally, we take into account additional three different parameters in our simulations, namely, traffic model, vehicle density, and average speed. More specifically, we consider *city* and *rural* traffic models, employ 200 and 300 vehicles to represent different vehicle densities, and use two different vehicle speeds, i.e., 40 and 80 mi/h. We perform extensive simulations with different simulation settings, as shown in Fig. 6. From the given results, we can observe that the proposed scheme can also achieve a higher performance than the competing methods. We also simulate the proposed schemes using some media-aware

TABLE IV
PERFORMANCE COMPARISON FOR DIFFERENT SCHEMES IN DIFFERENT SCENARIOS

| Scenario-1 | MASF | | CDCU | | DDA | | CSA | |
|-------------|---------------------------|---------------------------------|---------------------------|---------------------------------|---------------------------|---------------------------------|---------------------------|---------------------------------|
| | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation |
| time-slot 1 | 105.6 | 17.8 | 106.2 | 25.4 | 92.1 | 23.4 | 95.2 | 21.6 |
| time-slot 2 | 135.8 | 3.1 | 137.1 | 4.4 | 112.2 | 3.7 | 120.8 | 3.3 |
| time-slot 3 | 131.8 | 3.3 | 132.3 | 5.0 | 117.5 | 3.9 | 119.8 | 4.3 |
| time-slot 4 | 133.3 | 3.7 | 134.0 | 5.8 | 114.8 | 4.3 | 118.5 | 4.6 |
| time-slot 5 | 132.1 | 3.5 | 132.2 | 6.3 | 119.5 | 4.0 | 117.8 | 4.3 |
| time-slot 6 | 130.4 | 2.9 | 131.3 | 5.9 | 118.6 | 4.3 | 120.7 | 4.8 |

| Scenario-2 | MASF | | CDCU | | DDA | | CSA | |
|-------------|---------------------------|---------------------------------|---------------------------|---------------------------------|---------------------------|---------------------------------|---------------------------|---------------------------------|
| | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation | Average User Satisfaction | Satisfaction Standard Deviation |
| time-slot 1 | 190.4 | 25.2 | 190.8 | 40.3 | 182.0 | 37.3 | 178.7 | 39.8 |
| time-slot 2 | 241.1 | 3.7 | 241.8 | 4.0 | 223.1 | 3.9 | 227.5 | 3.7 |
| time-slot 3 | 237.9 | 2.8 | 238.7 | 4.8 | 220.2 | 4.2 | 219.1 | 3.5 |
| time-slot 4 | 232.1 | 2.9 | 232.7 | 5.3 | 221.5 | 4.2 | 221.5 | 4.4 |
| time-slot 5 | 237.0 | 3.0 | 237.3 | 4.1 | 223.2 | 3.9 | 227.5 | 3.5 |
| time-slot 6 | 237.9 | 2.5 | 238.8 | 5.2 | 216.5 | 4.5 | 223.2 | 4.6 |

metrics (i.e., average service time, average rejection ratio, etc.), and similar results can be achieved. Due to page limitations, we do not show them here.

VI. CONCLUSION

In this paper, we have develop a distributed heterogeneous media-service scheme that jointly solves the content dissemination, cache update, and fairness problems for P2P-based vehicular networks. Importantly, unlike conventional media-service schemes that focus on optimal quality of service or throughput, our work aims at achieving maximal user-satisfaction and certain fairness by jointly considering media-aware distribution and opportunistic transmission. Extensive simulation results have been provided, which demonstrate the effectiveness of our proposed schemes.

For practical heterogeneous media services over vehicular networks, additional work needs to be developed to estimate user-satisfaction implicitly from vehicle feedback instead of assuming that it is known, to develop a media content retrieval scheme to satisfy the heterogeneous media-service system, and to study an optimal media-service scheme with blind vehicle meeting information and media content updates. In our ongoing work, we plan to carefully address these open problems and study their impact on the actual vehicular networks.

APPENDIX A PROOF OF THEOREM 1

We first derive the probability distribution function of A_m for each $m \in \mathcal{M}$. Suppose that a media service m exists at time t , for age $q \geq 0$; let $K_q = \inf\{t | A_m(t) \leq q\}$ be the first time for which a media service m at least has age q . Then, for $t \geq 0$

$$\mathbb{P}(A_m(t) < k) = \mathbb{P}(K_q > t) \leq \mathbb{P}\left(\sum_{k=1}^{q-1} \mathcal{B}_k > t\right) \quad (23)$$

where \mathcal{B}_k ($1 \leq k < q$) are independently distributed exponential random variables with parameters β_k given by $\beta_k = k\mu\tilde{X}_m$. Let $T_q = K_{q+1} - K_q$ ($q \geq 1$) be the time between two consecutive increases of $A_m(t)$, and let $K_q = \sum_{k=1}^{q-1} T_k$. Suppose that (23) is true for $q = k$, when $k > 1$. Hence, we have

$$\begin{aligned} \mathbb{P}(K_{k+1} \geq t) &= \mathbb{P}\left(\sum_{q=1}^k T_q \geq t\right) = \mathbb{P}(T_k + K_k \geq t) \\ &= \int_0^\infty \mathbb{P}(T_k \geq t - s | K_k = s) d_m(s) ds. \end{aligned}$$

Conditioned on $A_m(t)$, T_k is independent of K_k . Hence, we have

$$\begin{aligned} \mathbb{P}(T_k \geq t - s | K_k = s) \\ = \sum_A \mathbb{P}(T_k \geq t - s | A_m(t) = A) \cdot \mathbb{P}(A_m(t) = A | K_k = s). \end{aligned}$$

We thus obtain $\mathbb{P}(T_k > t | A_m(K_k) = A) \leq e^{-t\beta_k}$. Since β_k only depends on k , we have

$$\mathbb{P}(T_k > t - s | K_s = s) \leq e^{-\beta_k(t-s)}, \quad s \leq t.$$

Using the above bound and applying Fubini's theorem [30], we find

$$\mathbb{P}(A_m(t) \geq k) \geq (1 - e^{-\mu\tilde{X}_m t})^{k-1}, \quad k \geq 1; \quad m \in \mathcal{M}.$$

Now, we obtain the probability distribution function of m 's average age; we use the decomposed function (10) to model

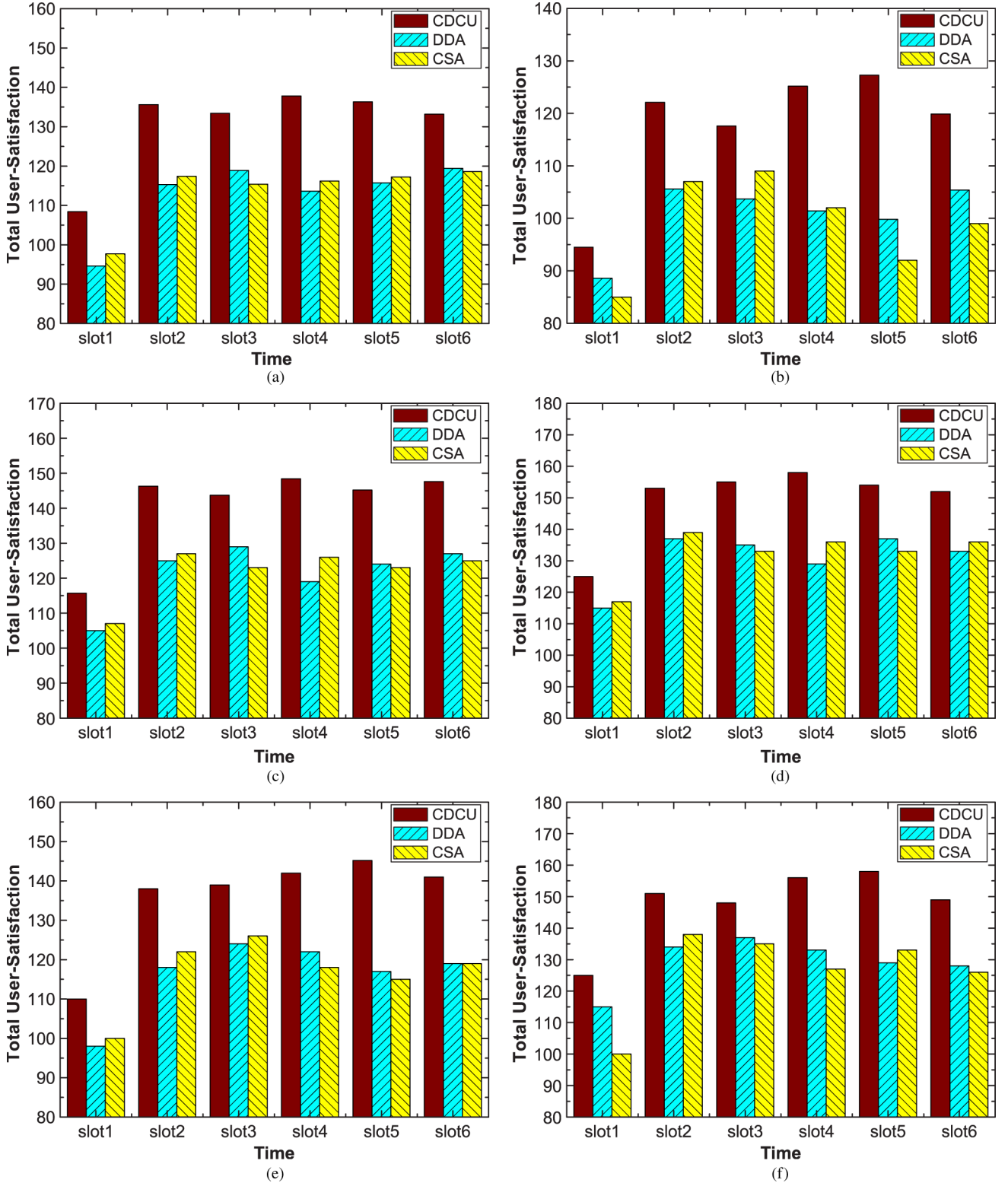


Fig. 6. Performance comparison under different network settings. (a) City traffic model. (b) Rural traffic model. (c) Number of vehicles is 200. (d) Number of vehicles is 300. (e) Vehicle speed is 40 mi/h. (f) Vehicle speed is 80 mi/h.

a dedicated user, i.e.,

$$G(\tilde{\mathcal{X}}) \propto \sum_{m \in \mathcal{M}} R_m \left(h_m(0^+) - \int_0^\infty A_m(t) d_m(t) \right). \quad (24)$$

This equation shows that $(\partial G / \partial \tilde{X}_m)(\tilde{\mathcal{X}}) = (R_m / A_m) \varphi(\tilde{X}_m)$, where φ is defined in Theorem 1. Assume that $\tilde{X}'_m < |\mathcal{V}|$,

$\tilde{X}'_n < |\mathcal{V}|$. If we have $R_m \cdot \varphi(\tilde{X}'_m) < R_n \cdot \varphi(\tilde{X}'_n)$, then there exists $\epsilon > 0$ such that

$$\begin{cases} \tilde{X}''_n = \tilde{X}'_n + \epsilon \\ \tilde{X}''_m = \tilde{X}'_m - \epsilon \\ \tilde{X}''_o = \tilde{X}'_o, & \text{for } o \neq m; \quad o \neq n. \end{cases}$$

This contradicts the optimality of \tilde{X} and proves that the equilibrium condition holds. ■

APPENDIX B PROOF OF PROPOSITION 1

According to the characteristic of decomposing $G(\mathcal{X})$, we define two optimization problems with variable $Z = c \cdot |\mathcal{V}|$, i.e.,

$$\begin{aligned} \text{OP1}(Z) : & \max \sum_{m \in \mathcal{M}} \sum_{x \in \{1, 2, \dots, X_m\}} G'_m(x) \\ \text{s.t. } & 1 \leq X_m \leq |\mathcal{M}|; \quad \sum_{m \in \mathcal{M}} X_m \leq Z. \\ \text{OP2}(Z) : & \max \sum_{m \in \mathcal{M}} \sum_{x \in \mathcal{I}_m} G'_m(x) \\ \text{s.t. } & 1 \leq |\mathcal{I}_m| \leq |\mathcal{M}|; \quad \sum_{m \in \mathcal{M}} |\mathcal{I}_m| \leq Z. \end{aligned}$$

The problem OP1(Z) is the problem we need to solve. The problem OP2(Z) is defined to assist the proof. Note that OP2(Z) can be viewed as a general case of OP1(Z) since it does not need to know the sum of G'_m on contiguous integers. According to [26, Th. 3.3–3.9], we have the following two observations.

- 1) *Observation 1:* We first define $\mathcal{I}_m = \{1, 2, \dots, X_m\}$, where $\{X_m | m \in \mathcal{M}\}$ and $\{\mathcal{I}_m | m \in \mathcal{M}\}$ are the solutions of OP1(Z) and OP2(Z), respectively. If the functions G'_m are nonincreasing for all m , OP1(Z) is equivalent to OP2(Z). It can be observed that \mathcal{I}_m is made of contiguous integers. If not, it is easy to construct another \mathcal{I}_m to maximize OP2(Z) (for the corresponding construct method, see [26, Lemmas 3.3–3.5]). Therefore, OP1(Z) and OP2(Z) are equivalent, and Observation 1 holds.

- 2) *Observation 2:* Let $\{\mathcal{I}_m | m \in \mathcal{M}\}$ and $\{\mathcal{E}_m | m \in \mathcal{M}\}$ be the solutions of OP1(Z) and OP2($Z + 1$). Hence, $\mathcal{I}_m \subseteq \mathcal{E}_m \forall m \in \mathcal{M}$, and the only n such that $\mathcal{I}_n \neq \mathcal{E}_n$ satisfies

$$n = \arg \max \left\{ \max_{x \notin \mathcal{I}_m} G'_m(x) \mid m \in \mathcal{M}, |\mathcal{I}_m| < |\mathcal{V}| \right\}.$$

It can be observed that \mathcal{I}_m is not equivalent to \mathcal{E}_m ; therefore, there exist n and u such that $u \in \mathcal{E}_n$ and $u \notin \mathcal{I}_n$. Define $\bar{\mathcal{E}}_n = \mathcal{E}_n \setminus \{u\}$ and $\bar{\mathcal{E}}_m = \mathcal{E}_m$ for all $n \neq m$; thus, all the subsets $\bar{\mathcal{E}}_n$ for all $n \in \mathcal{M}$ satisfy the conditions of problem OP2(Z). By optimality of \mathcal{E} , we can get $\bar{\mathcal{E}}_m = \mathcal{I}_m$. Therefore, Observation 2 holds.

According to the aforementioned two observations, we can get the following result: When all functions G'_m for all m are nonincreasing, if $\{x_m | m \in \mathcal{M}\}$ and $\{y_m | m \in \mathcal{M}\}$ are the solutions of OP1(Z) and OP2(Z), respectively, then

$$\begin{cases} y_n = x_n + 1, & n = \arg \max_m \{G'_m(x_m + 1) | x_m < |\mathcal{V}|\} \\ y_n = x_n, & \text{otherwise.} \end{cases}$$

This can be viewed as the method for designing the optimal allocation for any cache size c . Specifically, constructing \mathcal{I}_m

needs $|\mathcal{M}|$ steps, and seeking the optimal value of X_m needs $c \lg(|\mathcal{M}||\mathcal{V}|)$ steps (according to [30, Th. 4.2]). Therefore, this can be implemented at most with $O(|\mathcal{M}| + c \lg(|\mathcal{M}||\mathcal{V}|))$ steps. ■

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