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Utility Maximization for Multimedia Data Dissemination in Large-scale VANETs

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Abstract—With the increasing demand of media-rich entertainment and location-aware services from people on the road, how to disseminate the multimedia data in large-scale Vehicular Ad-Hoc Networks (VANETs) efficiently and reliably is a pressing issue. Due to the high mobility, large scale, and limited contact time between vehicles, it is quite challenging to support the multimedia data dissemination in VANETs. In this paper, we first utilize a hybrid framework to model the VANETs to address the mobility and scalability issues. Then, we formulate a utility-based maximization problem to find the best delivery strategy and select an optimal path for the multimedia data dissemination, where the utility function has taken the delivery delay, Quality of Services (QoS) and storage cost into consideration. With rigorous analysis, we obtain the closed-form of the expected utility of a path, and then obtain the optimal solution of the problem with the convex optimization theory. Finally, we conduct trace-driven simulations to evaluate the performance of the proposed algorithm with real traces collected by taxis in Shanghai. The simulation results demonstrate the rigorousness of our theoretical analysis, and the effectiveness of the proposed solution.

Index Terms—VANETs, Multimedia Dissemination, Utility Maximization, Quality of Services.

1 Introduction

The emerging of the auto operating systems (OS), such as Google Auto Link and Apple Carplay, have made a significant step to support more applications in Vehicular Ad-Hoc Networks (VANETs). Besides the emergency message applications, there is an increasing demand to provide multimedia services, such as media-rich entertainments, location-aware applications, traffic and road situation report, and advertisements in VANETs for the smart city scenario [1]–[6]. These multimedia applications depend on efficient and reliable multimedia data dissemination in VANETs. However, due to the randomness and high mobility of the vehicles (e.g., taxies), it is difficult to predict the movement of the vehicles. Meanwhile, since the contact time between vehicles is usually limited, a large-size multimedia message may not be fully transmitted between two contacting vehicles by vehicle to vehicle (V2V) communications only, which brings a new challenge. How to support efficient and reliable multimedia data dissemination in the large-scale VANETs is an important and challenging problem.

There are many existing works considering epidemic routing [7], [8], density based routing [9] or prediction based routing [10] to solve data dissemination problems in VANETs. Data can be carried and forwarded between vehicles, even in a network with high mobility and inherent intermittent connectivity. However, it may be too costly for multimedia message dissemination in large-scale VANETs. First, considering the huge number of vehicles in the urban large-scale VANETs, it is impractical to let each vehicle maintain a list of pair-wise contact probability and pattern, which is not scalable. Second, because of the relatively large size of multimedia messages, it is hard to replicate multiple copies and spray them following certain path given the dynamic and limited contact pattern and time. Third, within the short contact time, it is difficult to make a good data forwarding and routing strategy. On the other hand, although cellular networks can provide reliable data communication services, the high spectrum cost is a major concern, especially for bulk multimedia messages.

To address the above issues, recently, a scalable hybrid network framework has been proposed and adopted (e.g., [11]–[14]), combining the vehicle to infrastructure (V2I) and V2V communications for data dissemination in large-scale VANETs. This framework provides introduces Road Side Units (RSU) and drop-box to help data dissemination, and is scalable. We adopt a similar framework in this work. In our scenario, however, RSUs collect the vehicle's mobility information and help the vehicle carrying the multimedia message find other passing vehicles to forward the data. If the RSU can find an appropriate vehicle within the predetermined search time, the current message carrier will forward the data to the suitable vehicle using V2V communications. Otherwise, the data will be sent to the drop-box using V2I communications for temporary storing until an appropriate vehicle traveling along the desirable direction is found by the RSU. When the multimedia message is stored in the drop-box, it will render the storage cost. Considering the tradeoff of delay, QoS, and storage cost, we should find the optimal search time to decide when the data should be transmitted to the drop-box. Compared with the previous work, the main differences and novelties of this paper include: i) a practical objective function for multimedia message is considered, where the function depends on not only the delivery delay but also the QoS of the successfully delivered portion of the multimedia message and the storage cost in drop-boxes; ii) a new theoretical framework is provided to analyze the delivery delay, the multimedia utility and the storage cost; and iii) a utility-based optimal path selection and optimal transmission strategy at each node are proposed.

The main contributions of this paper are three-fold. First, we investigate a novel multimedia data dissemination problem for large-scale VANETs. The novelties of the problem include the consideration of the tradeoff of the delivery delay, the QoS of the successfully delivered data, and the storage cost, and the formulation of the utility-based maximization problem. Second, based on the rigorous theoretical analysis, we obtain the closed-form of the expected utility of a path, considering the delivery delay, the QoS of the multimedia message and the storage cost. We also use the convex optimization theory to obtain the optimal solution. Finally, the trace-driven simulation results demonstrate the rigorousness of the theoretical results. Compared with the existing solutions, the proposed algorithm can achieve much better performance for supporting multimedia applications.

The rest of the paper is organized as follows. In Section 2, the related work is summarized. Section 3 describes the system model and the problem formulation. We present the optimal upper bound and scheduling algorithm in Section 4. Performance evaluation by simulation is presented in Section 5, followed by the concluding remarks and further research issues in Section 6.

2 Related Work

Similar to other ad hoc networks, VANETs often suffer intermittent connectivity, while the moving vehicles can be used to carry-and-forward messages to the destinations. There are many works studying how to devise efficient and reliable routing algorithms for traditional delay-tolerant networks (DTN) or VANETs [7]–[10], [15]–[21]. Spyropoulos et al. [8] proposed the spray routing algorithm which extends the single-copy message routing to multiple-copy cases, and thus it can reduce the energy waste of the flooding type routing. Based on the analysis of the real bus traces, [15] proposed a route-level model with finer granularity to better predict the contact pattern between buses. Considering the dynamic and random connections, [20] applied the random linear network coding to the epidemic routing algorithms, and proved that it is efficient for delivering small amount of data. Zhang et al. [18] proposed a new geocast dissemination algorithm for urban VANETs with both taxi and bus. By dividing the whole VANET area into small regions, the mobility pattern can be predicted more accurately. Luan et al. [21] devised a practical infrastructure for large-scale VANETs. Distributed RSUs are deployed around the whole city without a central controller. However, these works request probing of neighboring vehicles frequently which results in high communication cost, and the QoS of the multimedia services was not addressed.

Recently, great efforts have been devoted for multimedia data dissemination [1]–[4], [14], [22]–[30]. Relying on the V2V communications, Soldo et al. [1] proposed a fully distributed live video broadcast algorithm to achieve high satisfaction and fairness. In [22], due to the limited contact time, the authors considered how to split the message into pieces and how to make a trade-off between the data size and the piece overhead. They devised a popularity based piece selection algorithm to solve the problem. To cope with the dynamic channel of VANETs, [26] presented a vehicle to infrastructure (V2I) based video transmission system with scalable video coding. In [3], [4], Rezende et al. proposed a receiver based density-aware video dissemination algorithm. The estimated location based relay selection process was decoupled from the video transmission process. To reduce the forwarding delay, Felice et al. [28] proposed a distributed beaconless routing protocol. V2V based high quality routes were maintained as the backbone for fast multimedia delivery. However, most of these existing works do not consider the tradeoff between the delay and the QoS of the multimedia services, which motivated this work.

3 System Models and Problem Formulation

In this section, we first describe the system scenario and models, followed by the problem formulation.

3.1 Network Scenario

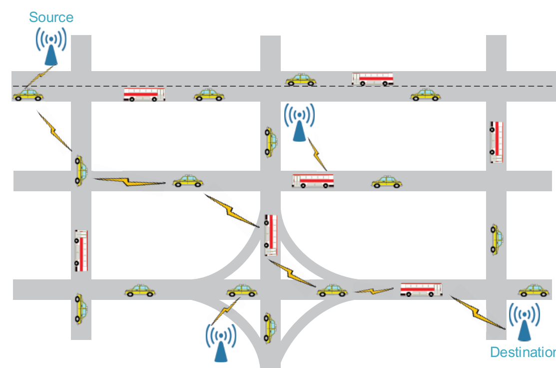


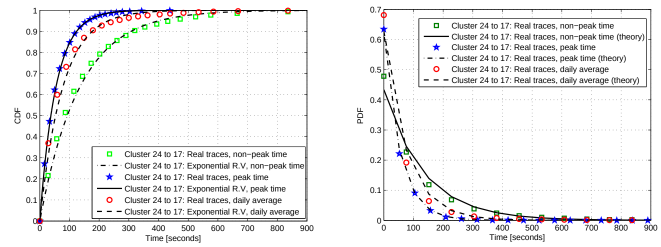
Fig. 1. Network for Multimedia Data Dissemination in VANET.

This paper investigates a multimedia data dissemination problem in VANETs, and the objective is to find a best path and the optimal strategy to disseminate different kinds of multimedia messages using vehicles (e.g. taxicabs) with the assistance of RSUs. As shown in Fig. 1, a multimedia message is generated at the source node, and carried and forwarded by the passing vehicles to the destination region. During the message transmission process, the multimedia message can be forwarded from one vehicle to another one by V2V communications. When one vehicle enters the coverage of an RSU, it will report its travel plan to the RSU, which is responsible for coordinating of V2V communications only. For a vehicle carrying a multimedia message, it will try to find the best candidate vehicle with the assistance of the RSU. If there is no appropriate vehicle to forward, i.e., it cannot find the vehicle in a given search time (which will be optimized in Sec. 4), it will transfer and store the multimedia message in a drop-box temporarily, and then rely on the RSU to find a future arriving vehicle to forward the data.

Similar to [21], RSUs are deployed at different locations around the whole city which is divided into regions. For each region, one RSU is deployed and the coverage area of the RSU is defined as a hot-spot. A unique identification will be assigned to each RSU. RSUs may or may not connect with each other, but the global RSU distribution information is available for all RSUs. In addition, a drop-box will be installed at each hot-spot as well for temporary storage of the multimedia message when the tagged vehicle cannot

TABLE 1
Important Notations

Symbol	Definition
T	the channel time
t_s	the search time
t_c	the transmission time
t_{ij}	the travel time from hot-spot i to j
λ_{ij}	the average arrival rate from i to j
U_D	the delay utility function
U_M	the video quality utility function
U_C	the cost function
R	the transmission rate between vehicles and infrastructure
Ω	the set of paths from s to d
Θ	the delivery strategy set



(a) CDF (b) PDF

Fig. 2. The CDF and PDF of the vehicle inter-arrival time.

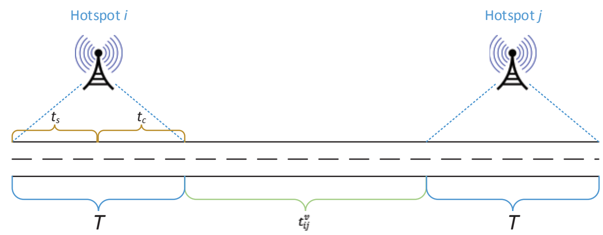


Fig. 3. Time definition.

find an appropriate passing vehicle to forward. The drop-box can be standalone storage devices without Internet connectivity, or the storage device of the parking vehicles in the hot-spot. With the large number of parking vehicles in the hot-spot, their storage and communication capacities are large enough to support heavy load. To better describe the the problem in this work, we abstract the whole city into a graph $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ and $\mathcal{E}$ are the set of vertexes and edges, respectively. Vertex $\mathcal{V}_i$ is considered as the RSU at the i-th hot-spot, and edge $\mathcal{E}_{ij} =< i, j >$ denotes the direct link from i to j, which is viewed as the traffic links between hot-spots. The vehicles traveling between two regions determine the link parameters, e.g., the vehicle travel time determines the propagation delay of the link and the vehicle arrival rate determines the latency from one link to the next one (similar to the queueing, processing and transmission delay in computer networks) along the path.

Table 1 summarizes the important notations in this paper for easy reference.

3.2 Vehicle Mobility Model

Vehicles have random mobility. With the analysis of traffic traces collected by taxis in Shanghai (partially available at http://www.cse.ust.hk/scrg), it is found that the vehicles traveling between two hot-spots is a Poisson process [13], [18]. Hence, the arrival of vehicles from hot-spot i to j is assumed to follow a Poisson distribution with the parameter λ_{ij} denoting the average arrival rate, which can be obtained from historical statistics. To verify the Poisson distribution assumption, we investigated the vehicle arrival pattern between the adjacent hot-spots by analyzing real traces. We obtained the distribution of the inter-arrival time of the vehicles traveling along each link, and compared it with the exponential distribution. All the inter-arrival times of the vehicles traveling from one hot-spot to another in one month are extracted from the traces. From the statistics of the inter-arrival time, we derive its CDF and PDF functions. It is found that the derived CDF and PDF match the exponential distribution quite well, which validates the Poisson arrival assumption. In Fig. 2, we plot the peak time (9 am–3 pm), non-peak (1 am–7 am) time and daily average CDFs and PDFs of the inter-arrival time from cluster 24 to 17. From the results, we can see that all the three CDFs and PDFs match the exponential distribution quite well. The Kolmogorov-Smirnov test results are 0.0471, 0.0187, and 0.0659 for non-peak time, peak time and daily average, respectively. For other links, we have similar results.

As shown in Fig. 3, let t_{ij}^v represent the travel time from hot-spot i to j, where the travel time inside the RSU's coverage is not included. Assuming that the coverage of each RSU is identical, and given the maximum traveling speed within the coverage of the RSUs, the minimum time that each vehicle can stay in the RSU's coverage is known, defined as T. Since the data transmission rate is limited and the size of multimedia message is relatively large, the transmission time of the multimedia message plays an important role. T is divided into two parts: searching time t_s (the time to find a vehicle to forward) and transmission time t_c (the time to transmit the data to drop-box for temporary storage), and $t_s + t_c = T$. Specifically, when the vehicle carrying the multimedia message enters the RSU's coverage, it will search a passing vehicle to forward during searching time t_s with the assistance of RSU. Then, the vehicle who is traveling to the desirable direction (obtained in the routing algorithm) and can receive enough amount of multimedia message ($\geq t_c R$) from the data carrier using V2V communications will be selected as the forwarder. If the tagged vehicle cannot find any vehicle to forward within t_s, then it will send the multimedia message to the RSU using V2I communications during the remaining time t_c. It should be pointed out that the transmission time t_c determines the minimum amount of multimedia message that can be transmitted, and it is the key factor of the optimal strategy for hot-spot. Thus, t_c is a key parameter to be designed in this work, aiming to make a tradeoff between the delay, multimedia quality, and storage cost. In the following, we discuss how to consider these three aspects using utility models.

3.3 Utility Model

As fast delivery is preferable, we define a utility function of the delivery delay to depict the benefit of fast dissemination, which is given by

$$U_D = F_d(T_{sd}), \tag{1}$$

where F_d is the delay utility function and T_{sd} is the random variable denoting the total delivery delay. F_d is assumed to be a monotonic decreasing function of the delivery delay, *i.e.*, a shorter delay will bring a higher utility.

Meanwhile, the multimedia message generated at the source node will be encoded first, e.g., videos may be encoded with H.264, Scalable Video Coding (SVC) or Compressed Sensing (CS) based codec. Since these multimedia codecs are typically error resilient and scalable, a certain level of packet losses may lead to degraded quality, but not corrupt the whole message. Thus, all the relays involved in the message delivery process will not discard the message even if a part of it is lost. However, with different encoding techniques, the amount of data required to decode certain quality video is different. Also, different different amount of data being delivered successfully may cause different user-perceived video quality. Therefore, we employ a utility model to map the total throughput of the multimedia message to the user's satisfaction level, similar to [31]. Mathematically, the video quality utility is modeled as

$$U_M = F_u^k(D), k = 1, 2, \ldots, N_e, \tag{2}$$

where F_u^k is the utility function for the k-th type of encoding technique, D is the total throughput which is a random variable depending on the forwarding strategies, and N_e is the total number of encoding techniques. The utility model (2) can take into consideration the relationship between user perceived quality (or user satisfaction level) and the amount of data being successfully received or lost.

In addition, if the tagged vehicle cannot find any passing vehicle to forward the multimedia message, it can send it to the drop-box for temporary storage, which will incur additional storage cost. Thus, we define the storage cost utility function as follows:

$$U_C = F_c(N_{sd}), N_{sd} \geq 0, \tag{3}$$

where F_c is the utility function for the cost, and N_{sd} is the total time of additional storage requests along the path.

By combining all the above utilities together, we defined the total utility function as

$$U = \alpha U_D + \beta U_M - \gamma U_C, \tag{4}$$

where α, β and γ are the weight parameters which can be adjusted according to user's preference. The weights of delay and video cost can be decided by the applications based on users' preference. For instance, for applications that can tolerate longer delay and requires higher video quality, we can set a larger value of β and a smaller value of α; and vice versa.

3.4 Problem Formulation

Assume that there are N paths from source s to destination d, and let $\Omega = \{p_{sd}^k | k = 1, 2, \ldots, N\}$ be the set of these paths. Define the delivery strategy set for the nodes by

$$\Theta := \{s(t) | t_c = t, 0 \leq t \leq T\}.$$

Note that a larger t_c can guarantee that the minimum amount of multimedia message can be transmitted is higher, i.e., a higher throughout, but may cause higher delivery delay and storage cost since the probability of the data transmitted to the RSU is increased. This is a trade-off between throughput, delay and cost. Therefore, we formulate a utility maximization problem as follows.

$$\max_{p_{sd}^k \in \Omega} \max_{s(t) \in \Theta} U = \alpha U_M + \beta U_D - \gamma U_C, \tag{5}$$

where U_D, U_M and U_C are defined respectively in (1), (2) and (3). By referring to [34], [35], the utility functions in the objective function are assumed to be convex and differentiable functions. Since the variables in the utility functions are random variables and thus the above problem is a random optimization problem. We further simplify this problem to maximize the expected utility as

$$\max_{p_{sd}^k \in \Omega} \max_{s(t) \in \Theta} E\{U\} = \alpha E\{U_M\} + \beta E\{U_D\} - \gamma E\{U_C\}. \tag{6}$$

The above maximization problem is still a convex optimization problem. To solve this problem, the main challenge is to obtain the closed-form of the utility. Then, we can use the general convex optimization approach, e.g., Lagrangian Multiplier, to obtain the optimal solution.

4 Optimal Delivery Strategy

To find the optimal path, according to our utility model, three factors need to be considered, the total delay, the multimedia quality and the storage cost. In this section, we obtain the closed-form of the total utility for any given path at first, and solve the stationary point of the utility to obtain the optimal strategy. Then, we compare the utility under the optimal strategy among all possible paths to find the optimal one for data forwarding. Finally, we design an algorithm to solve the utility-based maximization problem.

For simplicity, in the following subsections, we consider path p_{sd} (could be any path p_{sd}^k in set Ω) as the data forwarding path, and assume that there are n links along the path, i.e., $< i_0, i_1 >, < i_1, i_2 >, \ldots, < i_{n-1}, i_n >$, where $i_0 = s$ and $i_n = d$.

4.1 Analysis of the Expected Delay

There are two cases to estimate the expected link delay. First, consider the case that the vehicle carrying the multimedia message can find passing vehicle to forward in search time t_s ($t_s = T - t_c$). In this case, the multimedia message will be directly forwarded to a vehicle using V2V communications without additional delay. Then, the link delay equals the time of vehicle passing the RSU plus the traveling time, i.e., $T + t_{ij}^v$. Since the arrivals follow a Poisson process, the probability of this case is the probability that the vehicle carrying the message can find a vehicle going to j within t_s, i.e.,

$$Pr\{\tau \leq t_s\} = \int_0^{T-t_c} \lambda_{ij} e^{-\lambda_{ij}\tau} d\tau = 1 - e^{-\lambda_{ij} t_s}. \tag{7}$$

Second, consider the case that the vehicle cannot find an appropriate vehicle for data forwarding within time t_s at node i, the probability of such a case happening satisfies

$$Pr\{\tau > t_s\} = 1 - \int_0^{T-t_c} \lambda_{ij} e^{-\lambda_{ij}\tau} d\tau = e^{-\lambda_{ij} t_s}. \tag{8}$$

In this case, the multimedia message is transmitted to and stored at drop-box temporarily with transmission time t_c. After that, the RSU will find a vehicle going from node i to j, and then forward the data to that vehicle. Define t^w_{ij} to be the time of RSU finding a suitable vehicle for data transmission. Clearly, the PDF of t^w_{ij} is $\lambda_{ij}e^{-\lambda_{ij}\tau}$. Hence, the link delay in this case is equal to $T + t^w_{ij} + T + t^v_{ij}$, and the corresponding expected link delay satisfies

$$\int_0^\infty (2T + t^v_{ij} + \tau)\lambda_{ij}e^{-\lambda_{ij}\tau}d\tau = 2T + t^v_{ij} + \frac{1}{\lambda_{ij}}. \quad (9)$$

Combining the above two cases, it follows that the expected link delay satisfies

$$\begin{aligned} E\{T_{ij}\} &= Pr\{\tau \le t_s\}(T + t^v_{ij}) \\ &\quad + Pr\{\tau > t_s\}\left(2T + t^v_{ij} + \frac{1}{\lambda_{ij}}\right) \\ &= (1 - e^{-\lambda_{ij}(T-t_c)})(T + t^v_{ij}) \\ &\quad + e^{-\lambda_{ij}(T-t_c)}\left(2T + t^v_{ij} + \frac{1}{\lambda_{ij}}\right) \\ &= T(1 + e^{-\lambda_{ij}(T-t_c)}) + t^v_{ij} + \frac{e^{-\lambda_{ij}(T-t_c)}}{\lambda_{ij}}, \end{aligned} \quad (10)$$

where we have used the fact that $t_s = T - t_c$.

Since the Poisson process is time independent, the link delay between different links are independent with each other. Let T_{sd} be the delivery delay with path p_{sd}. It follows from (10) that the expectation of T_{sd} satisfies

$$\begin{aligned} E\{T_{sd}\} = \sum_{k=1}^{n} [T(1 + e^{-\lambda_{i_{k-1}i_k}(T-t_c)}) + t^v_{i_{k-1}i_k} \\ + \frac{e^{-\lambda_{i_{k-1}i_k}(T-t_c)}}{\lambda_{i_{k-1}i_k}}]. \end{aligned} \quad (11)$$

Using (11), it is not difficult to obtain the expected delay utility of a path when the utility function is given.

4.2 Analysis of the Multimedia Utility

It is obvious that the overall amount of the transmitted data is determined by the lowest throughput among all links in the transmission path. Based on path p_{sd}, there are two cases of the lowest throughput for data forwarding, which are analyzed respectively as follows.

When the data is transmitted to in one or more drop-boxes during the transmission, and the lowest throughput is t_cR, then the corresponding multimedia utility should be $U_M = F_u(t_cR)$. This lowest throughput is achieved if the vehicle carrying the multimedia message cannot find an appropriate vehicle to forward for at least one link along the transmission path. Since the probability of that for all links, the vehicle carrying data can find a suitable vehicle within time t_s is

$$\prod_{k=1}^{n}\int_0^{T-t_c}\lambda_{i_{k-1}i_k}e^{-\lambda_{i_{k-1}i_k}\tau}d\tau = \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right),$$

the probability of $U_M = F_u(t_cR)$ satisfies

$$Pr\{U_M = F_u(t_cR)\} = 1 - \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right).$$

When there is always a candidate forwarding vehicle for all links along the path during the transmission process, then the throughput along the path is greater than t_cR. Then, we have $U_M > F_u(t_cR)$ since F_u is a monotonically increasing function of the throughput. The probability of $U_M > F_u(t_cR)$ satisfies

$$\begin{aligned} Pr\{U_M > F_u(t_cR)\} &= 1 - Pr\{U_M = F_u(t_cR)\} \\ &= \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right). \end{aligned} \quad (12)$$

In this case, to calculate the expected value of U_M, it is needed to obtain the PDF of the lowest throughput, which is a challenging problem. Suppose that τ_{ij} is the actual searching time at hot-spot i to the next hot-spot j, where $< i, j > \in p_{sd}$. Clearly, we have $0 < \tau_{ij} \le t_s$. Let $x = \max_{i=1}^{n}\tau_{ij}$. Then, the lowest throughput is $(T - x)R$ and $U_M = F_u((T - x)R)$. Let $f(x)$ be the PDF of x, which is also the PDF of $U_M = F_u((T - x)R)$. Using the fact that the PDF of a random variable can be obtained from taking derivative of its CDF, we obtain a lemma as follows, which provides the closed-form of $f(x)$.

Lemma 4.1. *Given path p_{sd}, the PDF of the searching time x is*

$$f(x) = \sum_{k=1}^{n}\left(\lambda_{i_{k-1}i_k}e^{-\lambda_{i_{k-1}i_k}x}\prod_{l=1,l\ne k}^{n}\left(1 - e^{-\lambda_{i_{l-1}i_l}x}\right)\right), \quad (13)$$

for $\forall x \in [0, T - t_c)$.

Proof. Based on the definition of PDF, one infers that

$$Pr\{U_M > F_u(t_cR)\} = \int_0^{T-t_c} f(x)dx. \quad (14)$$

From (12), we have

$$\int_0^{T-t_c} f(x)dx = \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right). \quad (15)$$

Note that t_c is a variable in $[0, T]$, which means that the above equation holds for any given t_c, where $0 \le t_c \le T$. Let $y = T - t_c$, it follows from (15) that

$$\int_0^{y} f(x)dx = \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}y}\right),$$

for $\forall y \in [0, T]$. Taking derivative of both sides of the above equation over y yields

$$\begin{aligned} f(y) &= \frac{d\left(\prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}y}\right)\right)}{d\, y} \\ &= \sum_{k=1}^{n}\left(\lambda_{i_{k-1}i_k}e^{-\lambda_{i_{k-1}i_k}y}\prod_{l=1,l\ne k}^{n}\left(1 - e^{-\lambda_{i_{l-1}i_l}y}\right)\right), \end{aligned} \quad (16)$$

for $\forall y \in [0, T]$. Hence, given $t_c \in [0, T]$, we have (13) hold. □

In (13), $\lambda_{i_{k-1}i_k}e^{-\lambda_{i_{k-1}i_k}x}\prod_{l=1,l\ne k}^{n}\left(1 - e^{-\lambda_{i_{l-1}i_l}x}\right)$ indicates the probability density that the searching time is equal to x exactly for link $i_{k-1}i_k$ along path p_{sd}, while for other $n - 1$ links, the waiting time is small than x. Since path p_{sd}

includes n links, there are n different independent cases that the waiting time for each link $i_{k-1}i_k$ is x. Hence, the PDF is the summation of all the different cases.

Combining the above discussions of the two cases, $E\{U_M\}$ is calculated by

$$\begin{aligned} E\{U_M\} &= Pr\{U_M = F_u(t_cR)\}F_u(t_cR) \\ &\quad + \int_0^{T-t_c} F_u((T-x)R)f(x)dx \\ &= \left(1 - \prod_{k=1}^{n}\left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right)\right) F_u(t_cR) \\ &\quad + \int_0^{T-t_c} F_u((T-x)R)f(x)dx. \end{aligned} \tag{17}$$

4.3 Analysis of the Cost Utility

For each node i, if the message is not transmitted to the drop-box for temporary storage during the transmission process, the cost is 0. Otherwise, it will cause a positive storage cost, denoted by $F_c(t_c)$.

Note that the probability that a vehicle carrying data cannot find a moving vehicle to forward, i.e., $t_s > T - t_c$, is equivalent to that there is no suitable vehicle coming in $T - t_c$ time. Then, we have

$$Pr\{t_s > T - t_c\} = 1 - \int_{t=0}^{T-t_c} \lambda_{ij} e^{-\lambda_{ij} t} dt = e^{-\lambda_{ij}(T-t_c)}.$$

Hence, the expected total storage cost satisfies

$$\begin{aligned} E\{U_C\} &= F_c(t_c) \sum_{k=1}^{n} Pr\{t_s > T - t_c\} \\ &= F_c(t_c) \sum_{k=1}^{n} e^{-\lambda_{i_{k-1}i_k}(T-t_c)}, \end{aligned} \tag{18}$$

which is the cost utility.

4.4 Dissemination Algorithm

From the previous three subsections, we obtain the closed-form expression of how to calculate the expected delay, the expectation of multimedia utility and cost utility. By combining them together, we can obtain the expression of the total expected utility of a path, i.e., the objective function of (6), which is given by

$$\begin{aligned} &E\{U\} = \alpha E\{U_D\} + \beta E\{U_M\} - \gamma E\{U_C\} \\ &= \alpha F_d \left(\sum_{k=1}^{n} \left(T(1 + e^{-\lambda_{ij}(T-t_c)}) + t_{ij}^v + \frac{e^{-\lambda_{ij}(T-t_c)}}{\lambda_{ij}} \right) \right) \\ &+ \beta \left(\int_0^{T-t_c} F_u((T-x)R)f(x)dx \right. \\ &\quad \left. + \left[1 - \prod_{k=1}^{n} \left(1 - e^{-\lambda_{i_{k-1}i_k}(T-t_c)}\right) \right] F_u(t_cR) \right) \\ &- \gamma F_c(t_c) \sum_{k=1}^{n} e^{-\lambda_{i_{k-1}i_k}(T-t_c)}. \end{aligned} \tag{19}$$

From (19), the transmission time t_c is the only variable that controls the total utility when the path is given. Therefore, we need to find an optimal transmission time t_c^* to determine the optimal strategy in each node, such that the total utility can be maximized.

Algorithm 1 Maximum-Utility Dissemination Algorithm

```
1: Input: The set of paths Ω = {p^k_sd | k = 1, 2, ..., N}
2: Output: The optimal path p*_sd and the corresponding
   optimal transmission time t*_c
3: procedure GETOPTIMALPATH(Ω)
4:     Set MaxUtility ← 0
5:     for each path p^k_sd ∈ Ω do
6:         Derive the expected utility E^k{U} by (19)
7:         Solve d(E^k{U})/d t_c = 0, and get the solution set T^k_c
8:         Get the optimal transmission time t^{k*}_c by (20)
9:         Get the maximum E^k_max{U} with t^{k*}_c
10:        if E^k_max{U} > MaxUtility then
11:            MaxUtility = E^k_max{U}
12:            p*_sd = p^k_sd and t*_c = t^{k*}_c
13:        end if
14:    end for
15:    return p*_sd and t*_c
16: end procedure
```

Theorem 4.2. *Suppose that the optimal transmission time is t_c^* which can maximize the total utility. If τ_c is the stationary point of $E\{U\}$, i.e., $\left.\frac{d(E\{U\})}{d\ t_c}\right|_{t_c=\tau_c} = 0$, then the optimal searching time t_c^* satisfies*

$$t_c^* = arg \max_{t_c=0,\tau_c,T} E\{U\},\ when\ \tau_c \in [0, T], \tag{20}$$

or

$$t_c^* = arg \max_{t_c=0,T} E\{U\},\ when\ \tau_c \notin [0, T]. \tag{21}$$

Proof. Since all the utility function is assumed to be convex function and τ_c is the stationary point, the value of $E\{U\}|_{t_c=\tau_c}$ must be an extreme point and be either a maximum or minimum value. For a convex optimization problem (the objective function is either a convex or a concave function), the maximum value can only be chosen from the boundaries or the stationary point. Hence, the optimal solution can be obtained from (20) or (21). □

Based on the above theorem, we can design the algorithm to solve the utility maximization problem (6). To solve this problem, we can first use the shortest-path algorithm to select several candidate paths which have the lowest expected delay to decrease the complexity, since a path with a much larger delay is unlikely to be an optimal path. The expected delay for a given path p_{sd}^k can be calculated with (11). Then, N paths with the lowest expected delay are selected as the candidate path set $\Omega = \{p_{sd}^k | k = 1, 2, \ldots, N\}$. With the candidate path set Ω, the optimal path and the corresponding optimal searching time will be computed, and the pseudo code of the algorithm is shown in Algorithm 1. Specifically, in Line 4, we initialize the maximum utility to 0. In Line 6-9, the expected utility and optimal transmission time for each path is computed. The optimal path and the corresponding transmission time is selected by Line 10-12.

Note that, the proposed algorithm assumes the scenario that the vehicle arrival rate will remain stable. Then with

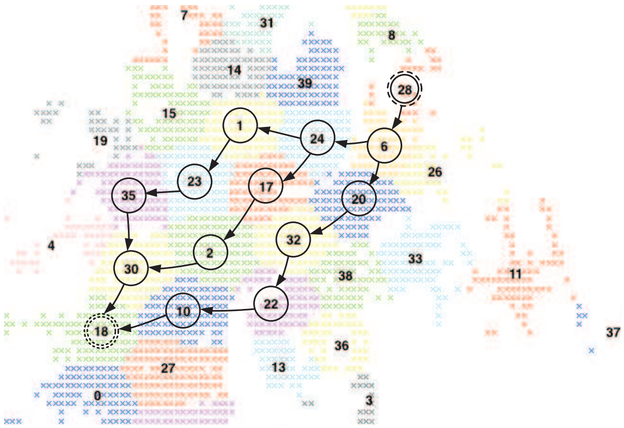


Fig. 4. Clustering of Shanghai map, with three paths selected from Wujiaochang (cluster 28) to Hongqiao airport (cluster 18).

the algorithm performed at the source node, the optimal path and corresponding optimal transmission time are determined. If the vehicle arrival rate varies with time for each hop, the proposed algorithm can be invoked at the hot-spot to capture the traffic dynamic.

5 Performance Evaluation

We conduct simulations with real traces to evaluate the performance of the proposed dissemination algorithm. For the trace analysis, we fist use Java to obtain the statistics of the vehicle traffic, and then we use MATLAB to conduct the trace-driven simulations.

5.1 Simulation Setting

To better evaluate the performance of the proposed algorithm, a practical setting based on the real trace collected from about 2,300 taxis in Shanghai between February and March 2007 is considered in this work. Similar to [13], [18], the whole Shanghai city area is divided into 40 regions based on the travel distance, which is shown in Fig. 4. The network topology is designed based on the clustering regions, and the RSUs are deployed as hot-spots at each region with the highest vehicle density. According to [32], the coverage radius and data rate for each RSU is set to 300 meters and 1 Mbps respectively for stable transmission, and the vehicle travel speed is set to 5 m/s as the urban scenario is considered. So, it is easy to calculate $T = 300 \times 2/5 = 120s$. The simulation ran with the vehicle arrival rate at different time of one day, and 1,000 runs were conducted for each case to obtain the average.

5.2 Utility Function

Delay Utility: First, by referring to [33], [34], the utility function of delay is given by

$$F_d = -c_1 \log \frac{T_{sd}}{T_{\max}}, \quad (22)$$

where T_{sd} is the delay for any given path p_{sd}, and $T_{\max}$ is the maximum tolerable delay. According to some preliminary results, the worst case of the delay is about the twice of the smallest delay, and thus we set $T_{\max} = 2\sum_{k=1}^{n}(T + t^v_{i_{k-1}i_k})$, c_1 is a weight parameter to balance the delay, multimedia quality, and cost utilities, and we set $c_1 = 10$ in the simulation.

Multimedia Data Utility: Second, a real video trace $football$ [36] encoded with two different types of video codecs (SVC and CS) are used as an example in our simulation. The discrete utility function (for SVC) and continuous utility function (for CS) are both evaluated, which are given as follows:

1) *Discrete utility function for multimedia message:* Since SVC encodes the video into layers with different quality, thus a stair-case utility function is modeled. The utility function is related to the PSNR of the SVC video with different layers. Similar to [31], the utility function for the video trace $football$ is express as:

$$F_u^{svc} = \begin{cases} 29.16, & 31.5 \text{ Mb} \le D < 56.13 \text{ Mb} \\ 33.27, & 56.13 \text{ Mb} \le D < 85.53 \text{ Mb} \\ 35.53, & D \ge 85.53 \text{ Mb} \\ 0, & \text{otherwise.} \end{cases} \quad (23)$$

2) *Continuous utility function for multimedia message:* When the video is encoded with CS technique, the video quality depends on the total amount of received video measurement. The utility function of the sample video $football$ can be express as:

$$F_u^{cs} = 0.51 D^{0.53} + 14.62. \quad (24)$$

Cost Utility: Third, the cost utility can be considered as the summation of the total number of temporary storage. Thus, we have

$$F_c = c_2 \sum_{k=1}^{n} e^{-\lambda_{i_{k-1}i_k}(T - t_c)}, \quad (25)$$

where c_2 is the weight parameter to balance the cost utility to the other two utilities, and $c_2 = 3$ in our simulation.

For the stair-case utility function, the calculation of the maximal $E\{U\}$ can be simplified, as only the boundaries and the turning points of the utility function need to be considered. While for the CS video, we need to find the set of values $\mathcal{T}_c$ which will make the derivative of $E\{U\}$ over t_c equal 0, which is easy to calculate. Then the optimal transmission time is obtained by (20).

5.3 Simulation Results

We conducted simulations based on the Shanghai traces. Since the clusters are divided based on the travel distance, we first set the travel time for each link $T_{ij} = 15$ minutes. The source and destination were set to cluster 28 (Wujiaochang) and cluster 18 (Hongqiao airport) respectively. Considering the large number of possible routes from the source to the destination, we selected three shortest paths by combining the Dijkstra's shortest-path and minimum delay derived by (11). The selected three shortest paths P1 $\{28, 6, 24, 17, 2, 30, 18\}$, P2 $\{28, 6, 24, 1, 23, 35, 30, 18\}$ and P3 $\{28, 6, 20, 32, 22, 10, 18\}$ are shown in Fig. 4. The peak time and non-peak time vehicle arrival rates (in the unit of per second) of the three paths were obtained from the traces,

TABLE 2
Vehicle arrival rates of the three shortest paths

	Peak time arrival rate
P1	$\{0.0050, 0.0024, 0.0185, 0.0503, 0.0249, 0.0253\}$
P2	$\{0.0050, 0.0024, 0.0142, 0.0188, 0.0146, 0.0045, 0.0253\}$
P3	$\{0.0050, 0.0160, 0.0197, 0.0133, 0.0021, 0.0042\}$
	Non-peak time arrival rate
P1	$\{0.0014, 0.0011, 0.0086, 0.0200, 0.0127, 0.0106\}$
P2	$\{0.0014, 0.0011, 0.0060, 0.0091, 0.0098, 0.0020, 0.0106\}$
P3	$\{0.0014, 0.0066, 0.0050, 0.0059, 0.0009, 0.0027\}$

which are shown in Table 2. To show the benefits of the proposed algorithm, we compare the proposed algorithm with the geographical-based routing algorithm, which has been widely adopted for VANET and been heavily investigated in existing works, e.g., [37], [38]. In addition, we compared the results with two simple algorithms, minimum-delay which tries to achieve the minimum delay with the lowest multimedia quality, and maximum-quality which only focuses on the highest multimedia quality while ignores the dissemination delay, to show the benefits provided by the proposed algorithm.

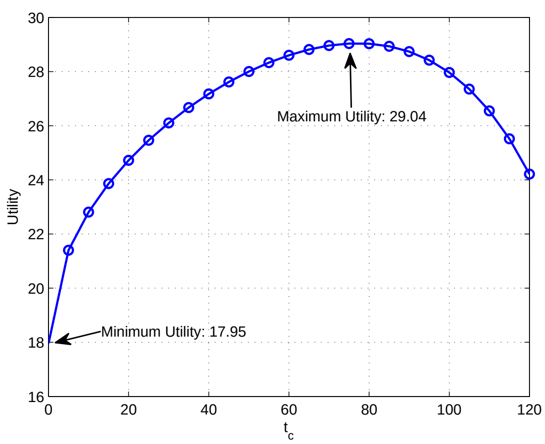


Fig. 5. The achieved utility versus transmission time t_c.

First, to show the necessity of the proposed algorithm, we evaluated the influence of the transmission time t_c to the final achieved utility. We tested the different settings of transmission time t_c and calculated the theoretical results of the utility for path 1, and the results are shown in Fig. 5. From the results, we notice that the maximum utility is greater than the minimum utility by 61.8%. The minimum utility is achieved when the transmission time $t_c = 0$, which corresponding to the case that the vehicle carried multimedia message never requests any additional storage help from drop-box. In this case, there is no guarantee for the minimum video quality, which will lead to low utility. While with the maximum transmission time $t_c = T$, whenever the tagged vehicle traveling by a RSU, it will request the additional storage services directly without waiting for other vehicles. Although high video quality can be guaranteed, long transmission delay and high cost will bring down the final utility. Therefore, the setting of transmission time t_c to the final achieved utility is crucial.

TABLE 3
Results of peak hours

		Theory	Simulation	Delay Minimized	Quality Maximized
SVC	P1	32.38	32.79	6.25	26.25
	P2	28.29	28.44	6.10	22.52
	P3	28.64	29.01	5.95	22.92
	Opt.	32.38	32.79	6.25	26.25
CS	P1	29.04	29.59	6.24	23.13
	P2	24.57	24.73	6.15	18.79
	P3	25.35	25.76	5.9	19.79
	Opt.	29.04	29.59	6.24	23.13

TABLE 4
Results of non-peak hours

		Theory	Simulation	Delay Minimized	Quality Maximized
SVC	P1	26.74	26.78	4.78	22.30
	P2	22.39	22.08	4.45	18.22
	P3	23.13	23.29	3.84	19.56
	OPT	26.74	26.78	4.78	22.30
CS	P1	23.68	23.70	4.67	19.36
	P2	19.58	19.51	4.46	15.49
	P3	21.73	21.70	3.98	17.18
	OPT	23.68	23.70	4.67	19.36

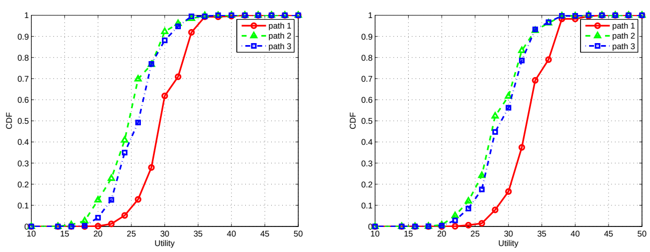
Second, we evaluated the performance of the proposed algorithm over the three selected paths, and the simulation results of the peak hours and non-peak hours are shown in Tables 3 and 4 respectively. These results were obtained with the parameter setting $\alpha = 1$, $\beta = 1$ and $\gamma = 1$. From these two tables, first we notice that simulation results match the theoretical results quite well, which demonstrate the correctness of the proposed algorithm. No matter at peak or non-peak time period, transmission along path 1 can always bring the highest utilities for both SVC and CS video. The reason is that the vehicle arrival rate of path 1 is slightly higher than the other 2 paths, which indicates lower probability of requesting additional storage from drop-box. Thus lower cost and higher final utility can be achieved. Since SVC encoding is more efficient than CS encoding, with the same setting, SVC video can bring higher utility than CS video. For the delay minimized algorithm, with the sacrifice of the video quality, the total delay does not reduce much, so very low utility can be achieved. While for the quality maximized algorithm, the high video quality incurred too many additional storage requests, and thus leads to lower utility than the proposed algorithm as well. By comparing Tables 3 and 4, the performance during peak hours can outperform that of non-peak hours, which is quite reasonable. With a higher vehicle arrival rate, there is a larger probability to find a passing vehicle to forward, and higher utility can be achieved.

Next, we compared the performance of the proposed algorithm with that of the geographical-based routing algorithm [37], [38]. Table 5 shows the performance of the geographical-based routing algorithm, where we used the same parameter setting ($\alpha = 1$, $\beta = 1$ and $\gamma = 1$). The geographical-based routing algorithm tends to choose the shortest path to transmit. With the help of Google Maps, it was a coincidence that path 1 was chosen as the shortest

TABLE 5
Results of the geographical-based routing algorithm

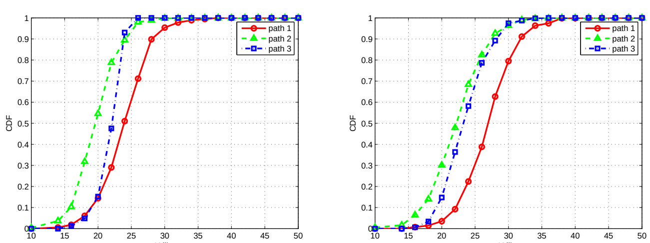
t_c		0	40	80	120
Peak hours	SVC	6.25	29.61	30.63	23.9
	CS	18.27	27.39	29.56	24.84
Non-peak hours	SVC	4.40	23.62	24.59	21.60
	CS	11.18	21.3	23.57	22.53

one. Since a geographical-based routing algorithm does not take the transmission time into consideration, we run the simulation with several different t_c settings. From the results, we notice that the geographical-based routing algorithm achieved a similar performance only with the optimal t_c setting. If setting an arbitrary value of t_c, using the existing geographical-based routing algorithm will result in substantial performance degradation. This confirms the importance of the design of t_c, which is the main focus in this paper. In addition, we need to point out that the shortest path cannot guarantee the best performance. The main reason is that if the shortest path has low traffic arrival rate, the high storage cost will lead to a low utility.



(a) CS encoded video (b) SVC encoded video

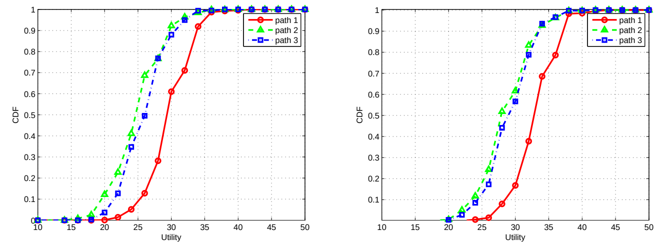
Fig. 6. CDF of utilities during peak hours.



(a) CS encoded video (b) SVC encoded video

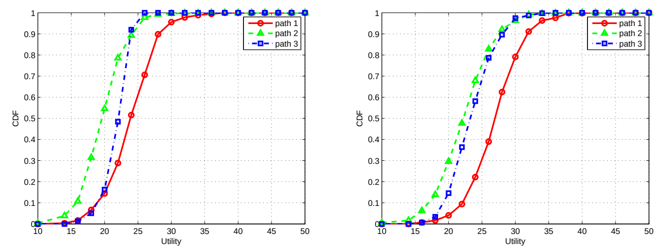
Fig. 7. CDF of utilities during non-peak hours.

To better show the performance over the three paths, we also plot the CDFs of the final achieved utilities of the three paths during both peak and non-peak hours, as shown in Figs. 6 and 7. From Fig. 6, path 1 has a much higher chance to achieve high utility than path 2 or 3. Paths 2 and 3 achieve similar results even through they have different number of hops. When the total traffic volume is reduced, as shown in Fig. 7, the chances to achieve a high utility is greatly reduced. In addition, during non-peak hours, path 3 has a slightly higher vehicle arrival rate than path 2, corresponding to a higher achieved utility.



(a) CS encoded video (b) SVC encoded video

Fig. 8. CDF of utilities with variation during peak hours



(a) CS encoded video (b) SVC encoded video

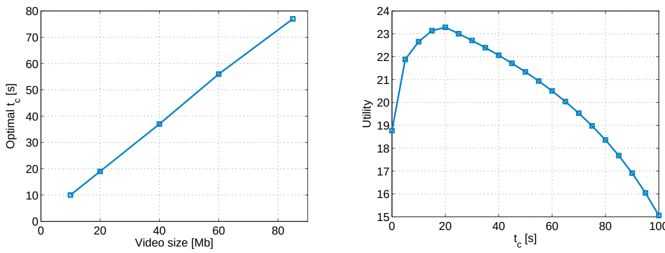
Fig. 9. CDF of utilities with variation during non-peak hours

In order to make the simulation settings more practical, we added random variations to the travel time of links between adjacent hot-spots, i.e., $t_{ij}^{+} = t_{ij}(1 \pm \varrho 10\%)$ (where t_{ij}^{+} denotes the random vehicle velocity), which can be viewed as the change of the vehicle speed. The results are shown in Figs. 8 and 9 for peak hours and non-peak hours respectively. By comparing the results with that of Figs.6 and 7, they achieve almost the same results, even with the 10% fluctuation of the travel time along links. From these results, it can be concluded that the proposed algorithm is robust to the fluctuation of the travel time along links, as it has limited impact on the overall performance.

Then, we investigated the effect of the different weight parameter (α, β, and γ) settings with three simulations. For each simulation, we only change one parameter to study the influence to the final utility, and the other parameters will be set as the default values ($\alpha = 1$, $\beta = 1$ and $\gamma = 1$), e.g, when α is changed, we keep $\beta = 1$ and $\gamma = 1$. The results are shown in Table 6 with four different parameter value settings. The top three rows of Table 6 show the results of different α. It can be noticed that by increasing the value of α, smaller optimal transmission time will be obtained. It is quite reasonable as shorter transmission time will lead to smaller delay. In the meantime, the utility will be scaled up with larger α as well. β indicates how important the video quality contributes to the final utility. In the middle three rows of Table 6, the optimal transmission time is increasing with the increment of β. As the transmission time guarantees the minimum video quality, longer transmission time leads to better video quality. For the penalty parameter, a larger γ will significantly reduce the chances of additional storage request. As shown in the bottom three rows of Table 6, lower optimal transmission time is obtained with a larger γ. Since lower transmission time means longer waiting time for passing vehicles to forward, and less additional

TABLE 6
The influences of weight parameters setting to results

α	1	3	5	10
Opt. t_c s	77.2 s	74.6 s	72 s	65.4 s
Opt. Utility	29.04	41.05	53.09	83.28
β	1	3	5	10
Opt. t_c	77.2 s	111.8 s	120 s	120 s
Opt. Utility	29.04	97.54	170.11	352.48
γ	1	3	5	10
Opt. t_c	110.4 s	77.2 s	59.3 s	34.3 s
Opt. Utility	36.38	29.04	23.74	13.15



(a) video size vs optimal t_c (b) video size is 20 Mb

Fig. 10. The performance under different video size.

storage requests are needed.

Finally, we changed the multimedia message size (from 10Mb to 85Mb) and investigated the impact of data size on the performance of the proposed algorithm. It is found that using the proposed algorithm can obtain the optimal path and the optimal t_c, and thus can obtain the maximum utility. Path 1 is still the optimal path for different settings of multimedia message size, while the optimal t_c is almost linearly decreased with the size as shown in Fig.10a. It is reasonable since when the data size is decreased, a smaller t_c can still guarantee a certain level of quality of the multimedia message. Meanwhile, it should be pointed out that for each setting of the data size, the maximum utility is much larger than the minimum utility at least by 30%. Fig. 10b shows an example when the data size is 20Mb. This again confirms the importance of the design of t_c.

6 Conclusion

In this paper, we have investigated a multimedia dissemination problem in large-scale VANETs under a hybrid framework. A utility-based maximization problem has been formulated to find the best delivery strategy, with the consideration of delivery delay, quality of the received multimedia message and the temporal storage cost. Then, we have obtained the closed-form of the utility functions. The maximization problem has been solved with a maximum-utility dissemination algorithm based on the convex optimization theory. Finally, we have conducted trace-driven simulations to evaluate the performance of the proposed algorithm.

There are still many open issues to investigate in the future. First, currently only one type of the general vehicles is considered in our work. More types of vehicles with different mobility patterns can be incorporated. Second, we set identical transmission time for all RSUs, while different transmission time settings for different RSUs should be explored, considering the different vehicle arrival rates. Third, the average vehicle arrival rate of each link is assumed constant in the current work, dynamic arrival rate should be considered and evaluated. Last, it will be an interesting research issue to further investigate strategies of separating the whole message into a few segments and a number of copies of each segment may be sprayed in the network.

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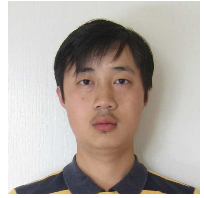

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