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Information-centric cost-efficient optimization for multimedia content delivery in mobile vehicular networks

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ABSTRACT

Providing high-quality multimedia services is a challenging and high-cost task in mobile vehicular networks due to intermittent connectivity, highly dynamic capacity, mostly associated to heterogeneous hosts distribution and their high mobility. Information-centric networking (ICN), which adopts novel content-based dissemination instead of the traditional host-based one, has great potential to accomplish cost-efficient quality-oriented multimedia delivery. This paper proposes a novel cost-Efficient Multimedia content Delivery approach (EcoMD) in vehicular networks leveraging the ICN features. In EcoMD, two essential factors are first analyzed and modeled: content mobility and supply-demand balance, and then, a mixed integer programming (MIP) optimization is formulated to minimize the economic cost associated to guaranteed the quality level of multimedia services. To resolve this NP-hard problem, heuristic mechanisms are proposed covering three aspects: priority-based path selection, least-required source maintaining and on-demand caching enhancement. By comparison with existing state-of-the-art solutions, simulation results demonstrate how EcoMD provides an improved performance in terms of start-up delay, jitter, playback continuity, and Quality of Experience (QoE) while particularly reduces the economic cost.

1. Introduction

According to the Cisco statistics, video in various forms will account for 80–90% of the global consumer traffic by 2017 [1]. Multimedia applications will become extremely popular in future. With the wide spread adoption of diverse mobile devices and wireless network technologies, it is both an opportunity and a challenge to deliver multimedia services (i.e. classic or 3D video, online gaming, street viewing, etc.) in mobile wireless network environments [2–4].

Lately, a variety of emerging wireless technologies such as WAVE/IEEE 802.11p, LTE, LTE-A, *etc.* have been developed to support multimedia delivery in vehicular networking via vehicle-to-infrastructure (V2I), vehicle-to-roadside unit (V2R) and vehicle-to-vehicle (V2V) communications [5–7]. Providing high-quality multimedia streaming services over Vehicular Ad-hoc Networks (VANET) has become a hot research topic [8]. However, most of the current research efforts did not consider the economic aspects when pursuing high quality multimedia delivery. For example, assuming that a WiFi access can support a low resolution video chat, it would involve higher costs if the same service is offered over a 4G/LTE channel. As video streaming is the largest contributor to the network traffic, it is of great interest to focus on cost-efficient high quality multimedia delivery [9,10].

The current network design puts the high quality multimedia delivery in difficulty when attempting to offer user services in high mobile networks [11]. The main problems and challenges include: (i) resources are usually associated with host locations which leads to poor support for high mobility users; (ii) connection-oriented sessions come with great control overhead due to the frequent changes of topology; (iii) different address spaces are adopted in heterogeneous networks which aggravates the management issues related to maintaining the address consistency. At the root of these problems is that the traditional host-to-host data exchange is not well suited to the frequently-moving video transfers in dynamic VANETs [12]. In this context, novel network architectures are considered to address these challenges [13].

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Information-Centric Networking (ICN) [14] has gained momentum as a candidate architecture for the future Internet. ICN focuses on "*what*" content users want to access instead of "*where*" the content resides, and tries to build novel *content-based* communication models, replacing traditional *host-based* ones [15]. This peculiarity allows the requester to retrieve content from the nearest providers, and avoids long routes to certain host addresses. Besides, the in-network caching performed at every ICN-based node has the potential to cope with the problem of intermittent connectivity [16,17].

By leveraging these features, ICN opens up many beneficial avenues for efficient multimedia delivery in highly dynamic VANETs. In our recent works, content delivery in ICN has been studied from diverse perspectives [18–20]. To the best of our knowledge, there are no specific works on cost-efficient approaches for multimedia delivery in VANETs. In this context, this paper proposes a novel approach for cost-Efficient Multimedia content Delivery (EcoMD) in vehicular networks by making use of information-centric data management means. The main novel contributions of EcoMD can be summarized as follows:

- EcoMD makes use of inherent multi-path, multi-source and multi-caching features in vehicular network environments.
- EcoMD is based on modeling the multimedia delivery process, considering two essential factors: content mobility and provider supply-demand balance. A mixed integer programming (MIP) optimization is formulated to minimize the economic cost associated to guaranteed quality levels for the multimedia services. The proposed MIP optimal problem is proven as NP-hard.
- EcoMD includes three newly designed heuristic solutions for the NP-hard problem focusing on finding sub-optimal solutions by considering (i) priority-based path selection, (ii) maintaining the least number of sources and (iii) on-demand in-path caching enhancement, respectively.
- EcoMD evaluation is based on extensive comparative simulation-based testing. The results demonstrate the efficiency of the proposed heuristic solutions and show how the proposed method outperforms other state-of-the-art solutions in terms of both quality-related and cost-efficiency-related metrics.

2. Related works

Several scientific contributions related to efficient multimedia delivery have been made recently [21–23]. Some of this research has addressed multimedia delivery over VANETs or emerging ICN. This section briefly discusses the most significant related works in the context of the research described in this paper.

Utilizing Peer-to-Peer (P2P) networks as platform for media streaming dissemination over VANETs is an attractive research topic. Naeimipoor et al. [24] proposed a hybrid video dissemination protocol that deploys a receiver-based relay node selection technique. Asefi et al. [25] proposed an adaptive medium access control retransmission scheme for video streaming over VANETs, which significantly reduced playback freezes while introducing a small increase in start-up delay. Rezende et al. [26] proposed a receiver-based solution, called REDEC, to conduct video transmission without the selection of relay nodes. Another protocol, VIRTUS [27], is proposed for video streaming over VANETs made use of the reactive aspects of receiver-based solutions to achieve performance improvements. Zhou et al. [28] developed a joint media service dissemination and cache update scheme in distributed manner for P2P-based vehicular networks. Our previous work [8] has also proposed an adaptive Quality of Experience (QoE)-driven user-centric Video on Demand scheme in urban multi-homed P2P-based vehicular networks. Despite all the solutions proposed, due to both unreliability and limited bandwidth in VANETs, providing high quality media streaming in VANETs remains a big challenge.

Table 1
Comparison of existing works.

	Multimedia	ICN	VANET	Economy
Multimedia in VANETs [22]-[28]	Yes	**Little**	Yes	**Little**
ICN for multimedia [29]-[37]	Yes	Yes	**Little**	**Little**
ICN for VANETs [38]-[39]	**Little**	Yes	Yes	**Little**
EcoMD proposed in this paper	Yes	Yes	Yes	Yes

The emergence of ICN has opened up a novel avenue to address quality-oriented video sharing issues and been proved to be a highly promising method. Detti et al. [29] introduced a P2P solution for live streaming of video content over the ICN, which increased the quality of video playback for small sets of neighboring devices. Lederer et al. [30] investigated the implementation of multimedia streaming within the ICN environment and integrated DASH and ICN. Piro et al. [31] undertook a thorough survey of the ICN-based multimedia systems and available tools, whereas Zhu et al. [32] proposed an audio conference tool for Named Data Networking (NDN). Han et al. [33] presented an adaptive retransmission scheme to overcome video packet losses in content-centric wireless networks. Liu et al. [34] performed an implementation of dynamic adaptive video streaming using a content centric networking approach. Additionally, Li et al. [35] proposed NF-DASH, an application-layer combined DASH and ICN solution for video traffic engineering. Detti et al. [36] presented a cooperative video streaming application running on top of ICN, whereas Li et al. [37] introduced a cooperative caching strategy for the treatment of large video streams with on-demand access. Although many researches contribute to the multimedia over ICN, most of them focus on video streaming over static network and do not consider the complexity of mobility scenarios such as those experienced in VANETs.

ICN-based communications over VANETs have also been researched [38–42]. Amadeo et al. [38] confirmed ICN's potential as a very promising networking solution for future VANETs, whereas Arnould et al. [40] proposed a new network architecture targeting hybrid VANETs based on an ICN architecture. TalebiFard et al. [41] adopted a selective random network coding approach and proposed a content-centric solution for information dissemination in vehicular network environments. Additionally, Wang et al. [39] applied the NDN concept in V2V communications, and proposed a data name design to develop a simple traffic information dissemination application. However, these proposals focus on general information dissemination, and do not consider the specifics of multimedia streaming applications, although these are highly important to be considered, as they are characteristics which significantly affect multimedia service quality.

Table 1 summarizes our related work investigation, and contrasts the proposed EcoMD with existing research in the areas of multimedia delivery in VANETs, ICN for multimedia and ICN communications in VANETs. It can be noted how very little research work focuses on the cost-efficiency in ICN-based multimedia delivery in VANET scenarios. Therefore, this paper fills this gap in the literature and introduces EcoMD, as a cost-efficient solution for information-centric multimedia streaming over VANETs.

3. EcoMD overview

EcoMD targets a realistic urban vehicular environment, in which vehicles are driven along the roads and inter-communicate, as illustrated in Fig. 1(a). Each vehicle accessing VoD services can obtain the desired video content from one of the following potential

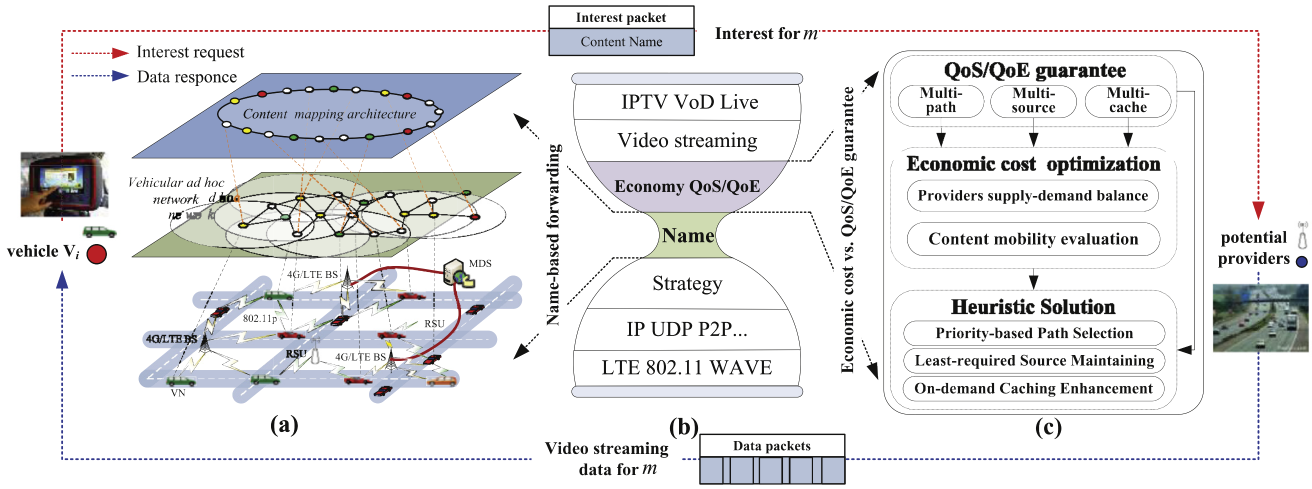


Fig. 1. Overview of the proposed solution: EcoMD.

providers: media delivery system (MDS), road side units (RSU) and vehicular nodes (VN). MDS can consist of a single server, a set of servers or a group of distributed streaming media proxies. RSUs are static network connectivity points, which can be enhanced to cache multimedia content. VNs are vehicles carrying multimedia content which move in the area and inter-communicate via a dynamic vehicular ad-hoc network.

Corresponding to three different communication types, three transmitting means are considered for multimedia content delivery: vehicle to infrastructure (V2I), vehicle to RSU (V2R) and vehicle to vehicle (V2V), respectively. Furthermore, each vehicle node is equipped with three interfaces (i.e. I-interface, R-interface and V-interface) which correspond to the three transmitting means, respectively. All the same type interfaces are connected or logically linked, and can be used to communicate with each other, via the respective communication means. Following this design, the interface selection determines the use of transmitting means. As they may be using diverse transmission protocols, the three communications means have different delivery performance and various cost-efficiency for any transmission process.

EcoMD employs a novel ICN-based networking model which is illustrated in Fig. 1(b). Different from the TCP/IP protocol stack, EcoMD adopts name-based forwarding instead of the address-based one, which moves the concern of the network stack from IP addresses to content names. Therefore, in EcoMD, the requester only focuses on what the desired content is, and does not care where it is located. As shown in the figure, name-based forwarding is at the core. In the underlying layers, the available individual links are such organized to support name-based forwarding, including physical links and transmission connections. This novel ICN-based networking can work as an overlay over any existing communication networks. For example, LTE can be used to support the physical links, and several address-based protocols such as TCP can be adopted for transmission connections. At upper layers, EcoMD performs video-related delivery based on the name-based forwarding and focuses on application-level strategies, such as the delivery efficiency (i.e. QoE and QoS) and economic cost.

In practical deployment, each node (i.e. vehicle or RSU) is equipped with an ICN forwarding engine with three different interfaces. This ICN forwarding engine plays an important role in the ICN-based data retrieval. For example, when a vehicle node has been told that it may retrieve a video via V2V means, the ICN forwarding engine sends out an Interest packet to request the content via its V-interface. Then, the next-hop vehicle nodes receiving the Interest packet further forwards it via their V-interface until the content is matched. Note that in EcoMD V2V communications support multi-hop data transmissions. Toyota *inc.* has already been working at developing such an ICN-equipped vehicular facility [43].

This ICN-based design supports EcoMD's focus on both cost-efficiency optimization and quality requirement for multimedia services. The detailed design of EcoMD is outlined in Fig. 1(c). EcoMD employs multi-path, multi-source and multi-cache functions. When availing from VoD services, vehicular users obtain the desired multimedia data immediately and are not concerned over which path or over how many paths the content is provided to them, as this is performed in the background. Multi-source refers to the fact that any content requesting vehicle can receive the multimedia data from multiple vehicle peers. This improves the service reliability, as another provider can step in if the current vehicle source fails to support the requested content delivery. At last, every vehicular node has the ability of caching multimedia data. Thus, a content can be cached in multiple locations. This enables the existence of multiple nodes as potential media providers.

The cost-efficient multimedia delivery of EcoMD over urban vehicular networks is summarized as follows. When a vehicle user wants to receive video content, an *Interest* packet is sent carrying the name of the desired content. When receiving the request, the potential providers including VN, RSU and MDS respond to the incoming request. Following the cost-efficient delivery decision of EcoMD, the video *Data* packets are transmitted from the distributed sources to the requesting vehicle user. In the following sections, the proposed EcoMD is detailed in terms of theoretical contribution and practical implementation.

4. System models

This section focuses on two key factors of EcoMD which greatly impact the cost-efficient performance: provider supply-demand balance and mobility evaluation of contents. Then, an MIP optimization is performed in order to minimize the economic cost for guaranteed quality levels. The EcoMD key notations and their definitions are listed in Table 2.

4.1. Providers supply-demand balance

Let us consider a scenario in which each video request can be handled by any of three kinds of delivery paths: V2V, V2I, V2R. The queue model is adopted to analyze the relationship between the video requests and quality levels. Its result is to calculate the playback delay for each kind of path, which will indicate which

Table 2
Key notations.

Multimedia	Definitions
$p_i(k)$	Probability of k users in the queue Q_i
ρ_i	Service utilization in Q_i
m	Video content $m \in \mathcal{M}$
λ_i, $\lambda_i{}^{(m)}$	Arrival rate for the queue Q_i, $Q_i^{(m)}$
μ_i, $\mu_i{}^{(m)}$	Service rate for the queue Q_i, $Q_i^{(m)}$
D_i, $D_i{}^{(m)}$	Average queue delay for Q_i, $Q_i^{(m)}$
α	A Zipf-like distribution parameter ($0 < \alpha < 1$)
L	Total number of video content items in $\mathcal{M}$
$s^{(m)}$	Size of $m \in \mathcal{M}$ (bits)
c_i	Cost of delivery per bit on delivery path i
q_i	Number of request responded by delivery path i
$bit^{(m)}$	Playback bit rate for the video content $m \in \mathcal{M}$
$y_j^{(m)}$	Binary variable indicating whether m is in $j \in V$
ξ_j	Caching capacity at $j \in V$
u_j	Upload bandwidth of the provider j
$\mathcal{U}$, $\Delta\mathcal{U}$	Total upload bandwidth, required upload bandwidth
$P_{s,d}$	Movement probability from cell R_s to R_d
A	Area of one location cell
π	Stationary transition probability matrix
$f(X_d)$	Stationary probability of content locating X_d
$\Gamma^{(m)}$	Content mobility evaluation factor for $m \in \mathcal{M}$
$X_s^{(m)}, X_d^{(m)}$	Source location and destination of vehicle with m
$\bar{N}_i$	Average number of request arrival in each path
$\bar{T}_i$	Average number of request served in each path
$\mathcal{C}_{v_i}, \mathcal{C}_o$	Central coordination of vehicle v_i and set o
$\Theta_i^{(m)}$	Content-associated transport capacity
$\tilde{N}$	Practical existing number of requests in the system
r_u	Required upload bandwidth for each extra request
n_c	the desired number of caches

path should be determined for users in order to playback the video content smoothly.

In order to estimate the average delay for user accessing the video content, each delivery path of V2V, V2I, and V2R is treated as an $M/M/1/\infty$ queue. Three kinds of providers are considered in this system: VN, RSU and MDS, which correspond to the three types of paths. In this queue model, we regard mobile users' requests for a video content $m \in \mathcal{M}$ as jobs in the queue system. Due to the bandwidth and storage limit, each kind of provider has a different service rate. Based on this, we build three queues for each video chunk and derive some characteristics which help us to make following analysis.

Let $Q_i (i = 1, 2, 3)$ denote the queue system with the provider VN, RSU or MDS. Let μ_i denote the service rate of each VN, RSU or MDS, and λ_i be the arrival rate for each queue. Therefore, $\rho_i = \lambda_i/\mu_i$ $(i = 1, 2, 3)$, is the service utilization in the queue Q_i.

To maintain the queue Q_i, we assume that $\rho_i < 1$, which means $\lambda_i < \mu_i$. As the queue Q_i is an $M/M/1/\infty$ queue, we can derive the probability of k users in the queue Q_i. The probability $p_i(k)$ is as follows:

$$p_i(k) = \rho_i(1 - \rho_i), (i = 1, 2, 3; k = 0, 1, \ldots, K) \tag{1}$$

According to the queue model, the average time for users to obtain the video is expressed by the average queue delay. Based on Eq. (1), the average queue delay for queue Q_i is as follows:

$$D_i = \frac{1}{\mu_i - \lambda_i}, (i = 1, 2, 3) \tag{2}$$

Assume $s^{(m)}$ is the size of each video content, $bit^{(m)}$ is the playback bitrate of video m, $Q_i^{(m)}$ is the queue to serve the content m delivery in path i, and $D_i{}^{(m)}$ denotes the average queue delay of content m in $Q_i^{(m)}$. Based on Eq. (2), we have the following inequality to guarantee the provider's supply-demand balance in path i to deliver the content m:

$$D_i{}^{(m)} \leq \frac{s^{(m)}}{bit^{(m)}}, (i = 1, 2, 3) \tag{3}$$

It means the video can be played smoothly in the queue $Q_i^{(m)}$, when average queue delay is less than the video content playback time.

According to the Eqs. (2) and (3), the request rate for m should satisfy the following inequality:

$$\lambda_i^{(m)} \leq \mu_i^{(m)} - \frac{bit^{(m)}}{s^{(m)}}, (i = 1, 2, 3) \tag{4}$$

This outcome provides a basic restricted condition for analyzing the minimal service cost, and will guide the system to adaptively adjust and manage the request rates for the three different queues to ensure the quality of multimedia delivery.

4.2. Content mobility evaluation

In this section, we evaluate the content mobility, which gives the most essential characteristic for an information-centric mobile network environment. Different from the node mobility, the content mobility is more complex. It is not only related to the mobility of vehicles, but also to the dynamic caching and replacing of contents. For instance, due to the content replacing, the location of one piece of content may change even when the vehicle does not move.

Consider a scenario in which vehicles move along the streets in both directions and make turns at cross-roads. Fig. 2 briefly illustrates the urban vehicular mobility scenario considered, and discretizes the 2-dimensional urban vehicular region for convenience of modeling. We consider a simplified vehicle mobility model, which stores vehicle movement direction, velocity and sojourn time. This triplet is used to define vehicle's mobility at any time. For example, each vehicle has to choose one of four directions to move towards (i.e. North, West, South, East), has associated a velocity value, and can also stop at any location for a while. For an instance as Fig. 2 shows, a vehicle at location (4,1) moves to location (0, 3) with a speed of 10 m/s, and then stops there for 5 s. Based on this, we can use location transition probability to analyze the vehicle's mobility.

The mobility pattern of vehicles can be seen as a set of consecutive movement periods in a closed region and the movement trace of each node is independent from the movement behavior of other vehicles. With the movement of vehicles, the location of one vehicle changes in region R, for instance, from location cell R_s to R_d. Let $P_{s,\,d}$ denote the movement probability from R_s to R_d. We can obtain a $K \times K$ transition probability matrix: $\mathrm{P} = \left[P_{s,d}\right]$. Therefore, the conditional density function of X_d given X_s is as follows:

$$f(X_d|X_s) = \frac{P_{s,d}}{A}, \text{if } X_s \in R_s, X_d \in R_d \tag{5}$$

where A denotes the area of one location cell, X_s and X_d denote the current position cell (source) and destination cell, respectively.

Therefore, the probability of the content moving to X_d can be described as follows:

$$f(X_d) = \frac{\sum_{s=1}^{K} P_{s,d}}{A} \tag{6}$$

Assume the mobility process is a Markov chain, we define a vector set $\pi = [\pi_1, \pi_2, \ldots, \pi_K]$ satisfying the following equation:

$$\pi \cdot \mathrm{P} = \pi, \sum_{i=1}^{K} \pi_i = 1 \tag{7}$$

Then, we obtain the stationary transition probability matrix π and the π_d for each cell.

Content popularity affects the frequency of content caching and replacing, which is important for evaluating the content mobility. Therefore, we first define the video content popularity as follows:

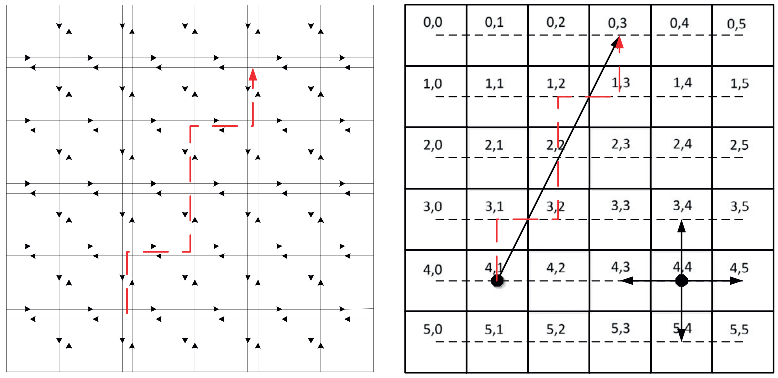


Fig. 2. (a) Urban vehicular scenario (b) Discretized urban region.

Definition 1. Video content popularity

Assume the multimedia content access rate follows a Zipf-like distribution, generally considered as representative of content popularity. Then, the popularity of video content $m \in \mathcal{M}$ is represented as follows:

$$P_o^{(m)} \triangleq \frac{1/m^{\alpha}}{\sum_{l=1}^{L} (1/l^{\alpha})} \tag{8}$$

where L denotes the total number of video content items in $\mathcal{M}$, and α ($0 \le \alpha \le 1$) is a Zipf-like distribution parameter. When $\alpha = 1$, the popularity follows strictly Zipf's distribution and the popularity follows the uniform distribution when $\alpha = 0$.

With above analysis, we define the content mobility evaluation factor $\Gamma^{(m)}$ for video content $m \in \mathcal{M}$, which is defined as follows:

$$\Gamma^{(m)} \triangleq \sum_{X_d^{(m)} \in R_d} \gamma \cdot \pi_d \cdot \left\| X_d^{(m)} - X_s^{(m)} \right\| \cdot \left(1 - P_o^{(m)}\right) \tag{9}$$

where $\| \cdot \|$ is the 2-norm operation, $X_s^{(m)}$ denotes the source location cell of the vehicle cache with the video content $m \in \mathcal{M}$, $X_d^{(m)}$ represents its destination location cell at the next time, and γ is a normalization factor.

The outcome will provide a reasonable content mobility evaluation for video content m in a time interval. It shows that the content mobility has a positive correlation with the node mobility, and a negative correlation with the content popularity. The content mobility will be used to evaluate the stability of service provision for a certain content.

4.3. Economic cost optimization

According to the above analysis about providers' supply-demand balance and mobility of different contents, the allocation of the request arrival rate to the three types of paths is a key problem to achieving cost optimization. In this section, we focus on the minimization of the economic delivery cost as the optimal objective, and the quality guarantee as the constraint conditions.

Formalizing, let $V_i (i = 1, 2, 3)$ denote the set of available providers in path i, $V = V_1 \cup V_2 \cup V_3$ be the set of all available providers to deliver the desired video content, $\mathcal{U}_i$ be the total upload bandwidth of path i, $u_j (j \in V)$ be the local upload bandwidth of provider j, ξ_j be the total cache size of provider j, and c_i is the cost of delivery per bit on path i. We formulate this multimedia delivery process in EcoMD as an MIP problem, which aims to deliver the desired video content using the lowest cost, while also satisfies the supply-demand balance and follows the available bandwidth and caching constraints.

$$\min \sum_{m \in \mathcal{M}} \sum_{i=1,2,3} \left(c_i \cdot \Gamma^{(m)} \cdot \lambda_i^{(m)} \cdot s^{(m)}\right) \tag{10}$$

subject to:

$$\lambda_i^{(m)} \le \mu_i^{(m)} - \frac{bit^{(m)}}{s^{(m)}}, \forall m \in \mathcal{M}, i = 1, 2, 3; \tag{11}$$

$$\mu_i^{(m)} \cdot s^{(m)} \le \mathcal{U}_i, \forall m \in \mathcal{M}, i = 1, 2, 3; \tag{12}$$

$$\sum_{m \in \mathcal{M}} s^{(m)} y_j^{(m)} \le \xi_j, \forall j \in V; \tag{13}$$

$$\mathcal{U}_i = \sum_{j \in V_i} y_j^{(m)} \cdot u_j, \forall m \in \mathcal{M}, i = 1, 2, 3; \tag{14}$$

$$y_j^{(m)} \in \{0, 1\}, \forall j \in V, \forall m \in \mathcal{M}. \tag{15}$$

Eq. (10) presents the main cost minimization objective. The constraint in Eq. (11) ensures the supply-demand balance to make video be played smoothly. The bandwidth limitation of path i is limited by the constraint in Eq. (12). The constraint in Eq. (13) ensures the contents one node carrying within its caching capacity. Eq. (14) states the definition of available upload bandwidth. The constraint in Eq. (15) states that the location $j \in V$ either has the video content $m \in \mathcal{M}$ or it does not.

Theorem 1. *The above MIP problem is an NP-hard.*

Baev et al. [44] consider a data placement problem where the objective is to minimize the cost, which has been proven NP-hard by the reduction from the metric incapacitated facility location problem. Our MIP problem is more complex, since we further consider additional constraint conditions, the content mobility and the supply-on-demand relationships between customers and suppliers, meaning that the proposed problem is also NP-hard.

As the system grows, solving this MIP problem may take an exponentially long time. Therefore, this approach cannot be used in a real-time manner on large cases. This motivates our decision to design heuristic algorithms to find approximate solution by making a number of practical considerations and parameters assumption. We propose a series of heuristic strategies to solve the problem in the following section.

5. Heuristic solution

In order to obtain a practical solution to the NP-hard problem, we follow a heuristic approach, which includes three stages: (1)

priority-based path selection, (2) least-required source maintaining, and (3) on-demand caching enhancement. This heuristic approach guides the system to obtain suboptimal solutions by making use of some reasonable assumptions and realistic conditions. Based on this mechanism, EcoMD achieves cost-efficient multimedia delivery with quality guarantee in polynomial time. The details of the three stages of the heuristic solution are presented next.

5.1. Priority-based path selection

In EcoMD, when one multimedia requester wants to download the video content, it sends out a request packet containing the name of the desired content. EcoMD provides three kinds of delivery paths, which have different cost and quality-related attributes. Thus, how to choose a cost efficient path to deliver video content should be considered first. Aiming to ensure the quality of multimedia delivery for end users using the cheap delivery paths, EcoMD employs a priority-based path selection algorithm to select suitable delivery paths.

To deploy the algorithm in a real environment, we use the average number $\bar{T}_i$ of requests served in each path to substitute the service rate, and use the average number $\bar{N}_i$ of request arrivals in each path per unit time to represent the arrival rate. Therefore, based on Eq. (2), the average delivery delay for a video content in each path can be calculated in practice as follows:

$$\bar{D}_i = \frac{1}{\bar{T}_i - \bar{N}_i}, i = 1, 2, 3 \tag{16}$$

In a video sharing system, the playback buffer in the requester should not be empty in the process of VoD playout, or the total upload rate should not be less than the specified playback rate if the playback buffer is empty.

Condition 1. In the worst case, there is only one video content downloaded in the playback buffer. Then, to playback the content smoothly, the following condition stands:

$$\bar{N}_i \leq \bar{T}_i - \frac{bit^{(m)}}{s^{(m)}} \tag{17}$$

Next, the main issue is how to select one of the alternative paths for multimedia data retrieval using the least cost for users. Before this, path costs need to be briefly discussed. In fact, the price plan for using different delivery networks is easily obtained from the network operators. In this paper, we consider flat prices as an example only, and this does not affect the performance of the proposed algorithm.

Without loss of the generality, we consider the cost of using the V2V path as the cheapest and using the V2I path as the highest one. There are two main reasons for considering this. First, unlicensed frequency spectrum can be adopted in 802.11p, which may be totally free for the V2V path, while the frequency spectrum must be licensed in 4G/LTE and involves a certain charge. Second, users need to pay for sharing content with neighbors over the V2V path only, while they must pay not only to the network provider, but also to the service provider when transferring data over the V2I path. The V2R path is believed to be an intermediate one.

In this situation, when performing path selection, the V2V path is considered first, then V2R and V2I at last. Algorithm 1 outlines the priority-based path selection policy in order to minimize the economic cost for a given quality level. One multimedia requester sends out the *Interest* packets which can carry the information of playback rate $bit^{(m)}$ and size of video content. The network system in EcoMD first calculates the $\bar{T}_i, \bar{N}_i, \bar{D}_i$ of each path. If the path V2V satisfies the Eq. (17), the V2V path is selected for multimedia delivery. If not, EcoMD continues to calculate the upload rate from the RSU peers, if Eq. (17) is met, then the V2R paths are chosen

Algorithm 1 Priority-based path selection mechanism.

while a request *Interest* for video content m is received **do**
  for each kind of path i **do**
    calculate the $\bar{T}_i, \bar{N}_i, \bar{D}_i$;
  end for
  if *Condition 1* is satisfied in path V2V **then**
    deliver video content m using the V2V path;
  else if *Condition 1* is satisfied in path V2R **then**
    deliver video content m using the V2R path;
  else if
    deliver video content m using the V2I path;
  end if
end while

as candidate path. If not, V2I path using the 4G/LTE is adopted for delivery video content for users. This provides a cost-efficient path selection policy.

5.2. Least-required source maintaining

After the delivery path is selected, managing the content providers needs to be considered next. When the V2V delivery path is determined, there are many candidate vehicular peers to select from to deliver the content data concurrently. The continuous delivery from multiple sources depends on maintaining of a number of reliable sources. Thus, the source management for each consumer is crucial to the performance of multimedia delivery. In fact, the delivery cost is related to the overhead of source maintenance, which is in direct proportion to the number of these sources.

In order to use the least sources, a suitable evaluation metric is needed for ranking the sources. Due to the content-based delivery in EcoMD, we consider the content distribution and content mobility as two key factors to determine the transport capacity of sources. A novel content-associated transport capacity for sources is proposed and defined to express the priority level of sources. This metric not only considers the available upload rate of the source, but also analyzes its potential upload opportunities for the following related content requests. The larger this metric value is, the higher the priority level is.

Definition 2. Content-associated transport capacity
The content-associated transport capacity $\Theta_i^{(m)}$ of source i delivering the video content $m \in \mathcal{M}$ is defined as follows:

$$\Theta_i^{(m)} = \omega_i \cdot \sum_{k=0}^{K} y_i^{(m+k)} \tag{18}$$

where ω_i denotes the available upload rate of the source i, $y_i^{(m+k)}$ is a binary variable indicating whether the source i has the video content $m + k$, which denotes the k-th related video content with m (has a chance to be requested in the near future), and K is the maximum number of related pieces of content considered.

According to the Definition 2, the higher upload rate the source provides, the higher priority level it has. Similarly, the more related video contents the source carries, the higher priority level it has. As for how to determine the pieces of video content related to m, there are advanced methods presented in the literature such as [45] and [46], but this is not in the scope of this paper. We consider a simple case that the video content pieces are requested and played in order, and the sequence number associated to any piece determines its relevance to the other video content pieces. Based on this assumption, when performing the source selection and maintenance, the sources with the highest priority levels are considered first, ensuring that the least number of sources are required.

Algorithm 2 describes the least-required sources maintaining

Algorithm 2 Least-required sources maintaining mechanism.

while a vehicle v_i in cell j requests for video content m **do**
  send out the request *Interest* for m;
  determine path to deliver m according to Algorithm 1;
  if $\Gamma^{(m)} \geq$ threshold **then**
    for each peer in the set of candidate peers $o^{(m)}$ **do**
      calculate the peer's priority level by formula (18);
    end for
  else if $\Gamma^{(m)} <$ threshold **then**
    for each peer in the set of candidate peers $o^{(m)}$ **do**
      calculate the peer's priority by $\left\|\mathcal{C}_{v_i} - \mathcal{C}_o\right\| \Theta_i^{(m)}$;
    end for
    sort peers in $o^{(m)}$ in descending order of the priority level;
    select least peers from $o^{(m)}$ to build $\Omega^{(m)}$;
    delivery video content m from $\Omega^{(m)}$ to v_i;
  end if
end while

mechanism for the V2V path. When a vehicle sends out the request *Interest* for content m, the following operations are conducted if the V2V path is selected (according to Algorithm 1). First, we determine the mobility of the content m, setting $\bar{\Gamma}^{(m)}=\frac{1}{2}$ as the threshold according to the outcome on an experimental study. If the mobility of the video content m is greater than this threshold, we calculate the priority level of candidate peers based on the content-associated transport capacity metric presented in Eq. (18). If the mobility of m is less than the threshold, we calculate the priority level of candidate peers based on $\left\|\mathcal{C}_{v_i} - \mathcal{C}_o\right\| \Theta_i^{(m)}$ to guarantee the contents are distributed more uniformly. Then, all peers are sorted according to their priority levels. This allows us to select a subset $\Omega^{(m)}$. The subset $\Omega^{(m)}$ includes the least-required sources, which have the relative higher content-associated transport capacity.

5.3. On-demand caching enhancement

Finally, we consider a possible situation. When there is a significant number of requests for one highly popular multimedia content, it results in a high economic cost and even poor quality due to the lack of cheap delivery paths and enough content providers with high $\Theta_i^{(m)}$. In this situation, efficient caching policies are very useful to alleviate this condition. In this context, we propose an on-demand in-path caching enhancement mechanism, which promotes the utilization of the cheapest V2V paths as well as enhance the quality of delivery by adjusting dynamically the number of vehicular content providers.

In the former analysis about providers supply-demand balance, we have shown how the expected arrival rate of requests $\lambda_i^{(m)}$ in the queue system should satisfy Eq. (4). However, when the existing arrival rate of requests $\tilde{\lambda}^{(m)}$ is much greater than any $\lambda_i^{(m)}$, $(i = 1, 2, 3)$, it means the requests will wait for a long time to be served no matter which path is selected. In this situation, one simple solution to reduce this time is to increase the number of available providers correspondingly. Based on its multi-cache function, EcoMD can increase the number of suppliers for a certain video content m on demand.

Due to the higher cost associated to the V2I and V2R paths in comparison with the V2V path, EcoMD focuses on improving the utilization of the V2V path to guarantee high quality levels. Caching the video contents in vehicular nodes provides a basic and efficient approach. However, greedy and arbitrary caching will waste the limited storage space and potentially increase the frequency of caching replacement. The key issue is how to conduct the caching process in EcoMD.

We adopt a simple but efficient method to determine the number of required caches based on the required upload rate. Let $\tilde{N}$ and $\bar{N}_i$ denote the total number of requests and affordable number of requests in path i, respectively. r_u is the required upload bandwidth for each extra request. Therefore, the required upload bandwidth can be calculated as follows:

$$\Delta\mathcal{U} = \left(\tilde{N} - \bar{N}_i\right) \cdot r_u \tag{19}$$

Condition 2. Due to differentiated upload rates in different nodes, the desired number of caches n_c should satisfy the following condition:

$$\sum_{i=1}^{n_c} u_i \geq \Delta\mathcal{U} \geq \sum_{i=1}^{n_c-1} u_i \tag{20}$$

where u_i denotes the upload bandwidth of a new caching provider i.

In the caching process, following the content request, the returned *Data* caches along the delivery path until satisfying Condition 2. The on-demand in-path caching enhancement mechanism is detailed in Algorithm 3. In EcoMD, when the V2I or V2R

Algorithm 3 On-demand in-path caching enhancement mechanism.

while a large number of requests for video content m **do**
  select path(s) from $\{V2V, V2R, V2I\}$ by Algorithm 1;
  if the V2R or V2I path(s) are selected **then**
    calculate the required upload rate $\Delta\mathcal{U}$ by formula (19);
    for each delivery path j of k selected paths **do**
      Data packet is returned carrying a counter Δ;
      initialize $\Delta \leftarrow \Delta\mathcal{U}/k$;
      for each node i in delivery path j **do**
        cache the *Data* packet locally;
        update the $\Delta \leftarrow \Delta - upband_i$;
      end for
    end for
  end if
end while

paths are adopted according to the path selection mechanism, we believe there is a need for the in-path caching to reduce the economic cost for the users. If an in-path caching is activated, the *Data* packet is returned carrying the information of additional required upload bandwidth. Then, each passing node first checks this information after receiving this data, and decide whether it caches this *Data* or not, and if so it updates the value of still required upload bandwidth. The in-path caching stops when the required upload bandwidth value becomes zero or less than zero. By leveraging the existing *Data* packets, this process provides a simple and low-overhead caching solution in EcoMD without introducing extra control packets.

6. Performance evaluation

6.1. Simulation settings

Network Simulator (NS-3) is employed to build our experimental platform, which required addition of mobility scenarios, protocol implementation, EcoMD modeling and simulation and scripts for result analysis. An external module named ndnSim [47] is

Table 3
General parameter setting.

Parameters	Values
Area	$2 \times 2(\text{km}^2)$
Mobile VN nodes	100–1000
RSU nodes	12
MDS node	1
Synchronous requesting users	10–100
Video segment average length	3 s
Total segment number	240
Min mobile speed	20 km/h
Max mobile speed	60 km/h
Traditional routing protocol	DSR
New routing protocol	CCNx
Transport layer protocol	TCP

Table 4
Key configurations in simulation.

Parameters		Values
LteHelper (eNB, UE)	Rx/Tx Power	46, 23 dBM
	Noise figure	5, 9 dB
	Mac channel Delay	5 ms
	Transm. distance	2 km
	UL/DL bandwidth	50/100 Mbps
	Fading model	Trace fading loss
	Operating frequency	2.5 GHz
	Data schedular	PfFf Mac schedular
	Transmission mode	MiMo Tx diversity
WifiHelper (RSU, UE)	Rx/Tx power	20, 10 dBM
	Noise figure	7, 11 dB
	Channel swith delay	250 ms
	Transm. distance	500, 300 m
	Bandwidth	2 Mbps
	OFDM eate	54 Mbps
	Wifi Mac	Adhoc Wifi Mac
	Operating frequency	5.9 GHz

added to implement the ICN communication model, which is a typical example of information-centric networking. Consider a Manhattan Grid topology with an area of 2×2 km^2, which consists of three horizontal and three vertical streets, and each one has two lanes in the two directions. BonnMotion mobility generator [48] is used to generate this realistic mobility scenario, which can be exported for NS-3. To evaluate user's QoE, we use a novel evaluation tool based on the NS-3, named QoE monitor [49], which takes charge of the multimedia quality assessment in our simulation.

An urban vehicular scenario is considered in our experimental testing, in which 100–1000 vehicles drive along a street, and 12 RSUs are deployed uniformly along the street with 500 m between each other. A 4G/LTE base station is located at the center of this area. In our simulations, we make sure each vehicle can connect with one RSU at any time and handover occurs when a vehicle moves from a RSU coverage area to another one. Detailed simulation parameter settings are shown in Table 3. Each vehicle is equipped with two kinds wireless interfaces: WiFi (i.e. *WifiHelper(UE)*) and LTE (i.e. *LteHelper(UE)*) and each RSU is equipped with WiFi Access Point and LTE Base Station support. The key configurations for these devices are listed in Table 4. Any other unlisted parameters used the NS-3 default values. The mobility of vehicles is considered according to the Manhattan Mobility model, and the maximum speed is 60 km/h. Each vehicle or RSU is equipped with a caching container, which manages the video segments it carries, including update and delete operations.

Regarding the traffic model, in order to simulate realistic video content sharing, we selected several synthetic user viewing log entries based on interactive actions, measurements and statistics from [50]. In details, the number of synchronous requesting users

Table 5
Selected video samples.

Video name	Description	Resolution		
akiyo	4:3 300 frames	–	CIF	QCIF
container	4:3 300 frames	–	CIF	QCIF
city	4:3 600 frames	4CIF	CIF	QCIF
crew	4:3 600 frames	4CIF	CIF	QCIF
harbour	4:3 600 frames	4CIF	CIF	QCIF
ice	4:3 600 frames	4CIF	CIF	QCIF
soccer	4:3 600 frames	4CIF	CIF	QCIF

is equal to the 10% of total mobile nodes. These mobile nodes join the system in terms of a Poisson distribution. When a user finishes downloading a specific video content, he will look for the next segment sequentially. Once one user finishes the playback of the whole video, he quits the system and another user will be selected.

Initially, all video segments are distributed to all vehicular nodes and RSUs uniformly. We assume that each vehicle carries 30 segments in their caching container at most by using a content list, and each RSU carries a maximum of 60 video segments. Once the container is full, the least recently used segment is replaced with a new one by least recently used (LRU) policy.

We select seven well-known video samples from [51] as the requested videos in the simulations. These videos have three formats with different resolutions. Their details are listed in Table 5. We use UltraVideoSplitter [52] to cut the video into segments. Each video is divided into many segments with constant length. The length of each video segment is 3 seconds long[1]. These video segments are uniformly named by "*{video name}_{resolution}_{sequence number}*", for example "*container_CIF_1*". This naming format is convenient for the name-based delivery in ndnSim. In total, 240 different video segments are collected.

In this experiment, we first verify the performance of EcoMD during solving process, and then compare EcoMD with two state of the art solutions VMesh [53] and QUVoD [8] in terms of both QoS and QoE levels. The QoS-related metrics include average start-up delay, playback freeze, and jitter. Some existing QoE evaluation metrics are also employed to estimate user perceived quality, such as PSNR, VQM, SSIM and MOS. Besides, we also analyze the cost-efficiency-related metrics including system control overhead, cost efficiency and utilization of different paths.

6.2. Results analysis

(1) Solving efficiency: In terms of solving efficiency, we evaluate the performance of EcoMD by making comparisons with both the optimal solution and a candidate solution with Evolutionary Game Theory (EGT), proposed by Niyato in [54]. Fig. 3 shows the comparison results in terms of average throughput. We can see that EcoMD can achieve a similar average throughput level (between 7–9 Mb) with the EGT. In particular, EcoMD achieves a better performance than EGT with 100, 200, 300, 500 and 700 vehicular nodes. What's more, the performance of EcoMD is more stable, because the data of EcoMD has a smaller jitter than the one of EGT. By comparing with the optimal solution, EcoMD is in close proximity to the optimal solution, especial when the number of vehicular nodes is small. We observe the performance of both EcoMD and EGT decreases as the number of nodes increases. This is because the computing complexity increases with the number of nodes. Based on the performance, we further compare the computing complexity in term of the time of solving process with

[1] The last segment of each video may be shorter than 3 seconds.

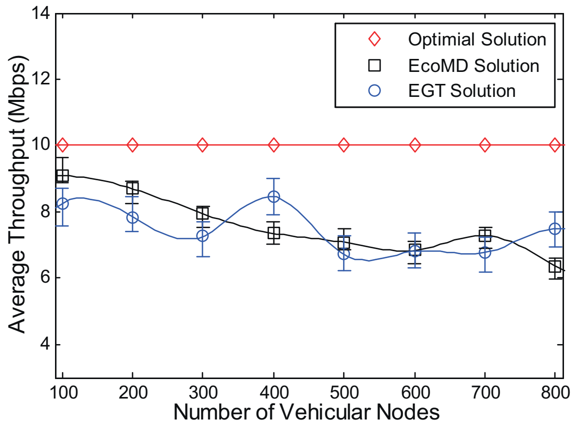


Fig. 3. Average throughput.

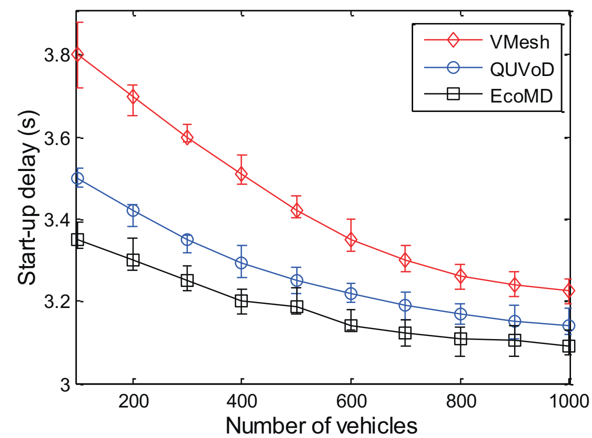


Fig. 5. Start-up delay vs. Nodes number.

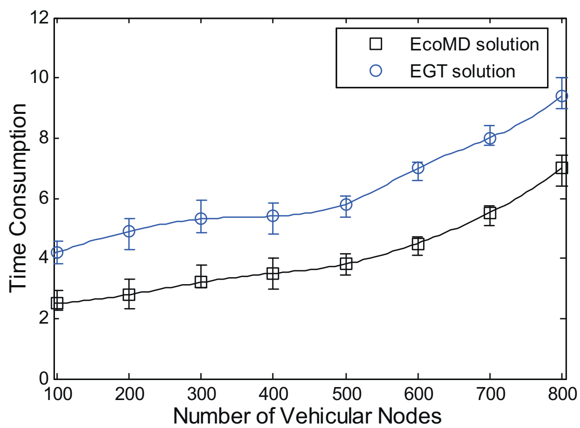


Fig. 4. Computation complexity.

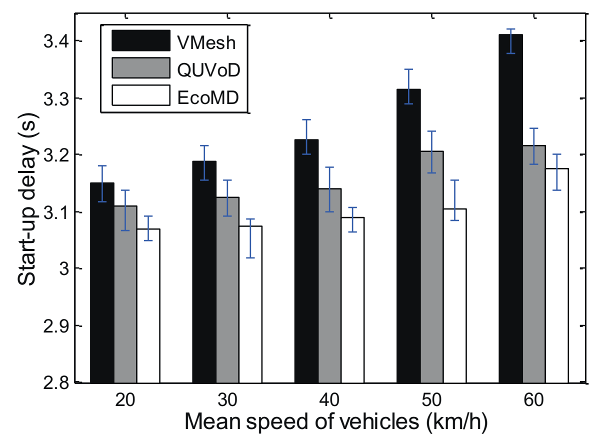


Fig. 6. Start-up delay vs. Mean speed.

EGT. The results are shown in Fig. 4. We observe that the time of solving process increase with the number of vehicle number in both EcoMD and EGT. The time consumption in EGT increases from 4 s to 9 s, while the one of EcoMD increases from 2.4 s to 6.7 s. In total, EcoMD consumes less time than the EGT by about 26%–40%. Thanks to the simple and efficient designs in heuristic algorithm, EcoMD enables the system to make decisions more easily and faster. On the contrary, EGT solution needs to broadcast the computation results during the solving process, which has a high complexity of computation for both the centralized controller and end users. Overall, EcoMD achieves 80% of ideal optimal throughput with little computation complexity.

(2) Start-up delay: Start-up delay in our simulation is defined as the latency from sending out the *Interest* packets to the starting of video when the playback buffer is full. Fig. 5 shows that the start-up delay varies with the number of vehicles. We observe the start-up delays in all three solutions (VMesh, QUVoD and EcoMD) decrease with the increase in number of nodes. It is easily understood that more vehicles create more content sharing chances for reliable video delivery. Therefore, vehicles can find a satisfying video supplier easier. It is noteworthy that the solution EcoMD has lower start-up delay than other two existing proposals, VMesh and QUVoD with 4.3–11.2% and 1.6-3.7%, respectively. The main reason is that three kinds of service paths in EcoMD are optionally available to choose better content providers according to the requester's demand. Moreover, in-path caching may pre-cache the video content actively based on its popularity, which enables to improve the utilization of potential content providers, while also further decreases the start-up time of playing video contents. We also analyze the mobility influence on the start-up delay. The moving speed is ranging from 20 km/h to 60 km/h, which are typical values for urban speeds. The simulation result is shown in Fig. 6. It is observed that start-up delays of EcoMD and QUVoD increase slightly with the vehicle moving speed. The main reason is that both EcoMD and QUVoD adopt more reliable architectures by leveraging the 4G/LTE communication means. The 4G/LTE has a larger coverage area, which is suit for long distance transmission, so it can relieve the effects due to vehicles' mobility. EcoMD has the least start-up delay among these three solutions. That is because the EcoMD adopts the priority-based path selection mechanism enabling to enhance the delivery performance. Moreover, in-path caching enables the vehicles to find satisfied content suppliers easier, which can reduce the searching time.

(3) Jitter: Jitter is used as a measure of the variability over time of the packet latency. In this paper, we define jitter of a packet as the delay variation relatively to the last packet of the stream, which is formalized as $\mathrm{Jitter}(P_n) = |\mathrm{Delay}(P_n) - \mathrm{Delay}(P_{n-1})|$. We trace the packet jitter during the video requesting from a certain vehicle (with a fixed node id) in different solutions. The result is shown in Fig. 7. As the figure shows, the mean jitter using VMesh is much higher than that of other strategies, mainly due to the high variability of connectivity between nodes in VANETs. QUVoD achieves a low jitter as it partially uses G-path for data delivery which can be negatively impacted by the unreliable connectivity. The EcoMD performs the best because the in-path caching and multi-source maintaining is able to guarantee the relatively reliable delivery paths to be selected in EcoMD. Additionally, we notice that many jitter "spikes" existed in three lines. With a careful

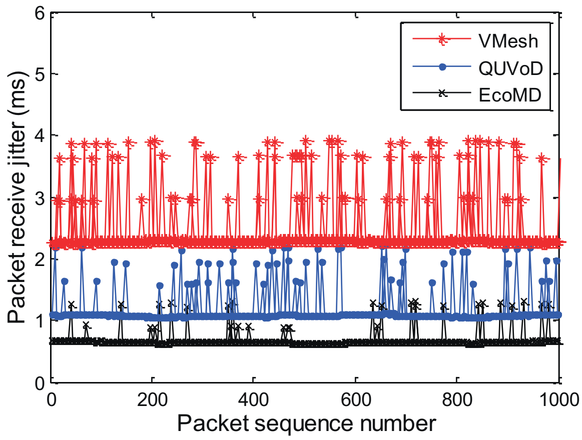


Fig. 7. Jitter vs. Packet sequence number.

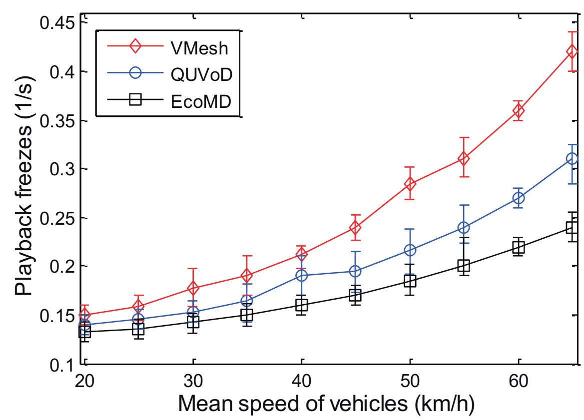


Fig. 9. Freezes vs. Mean speed of vehicles.

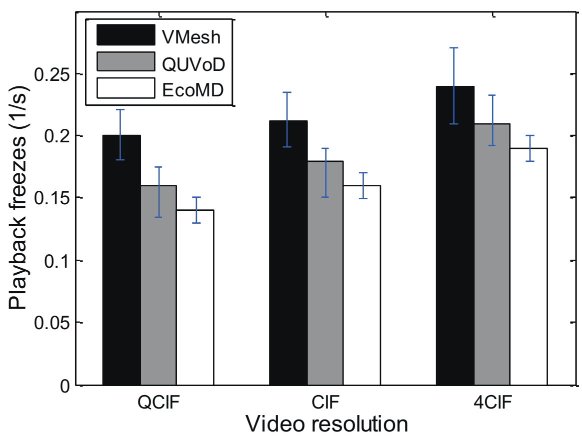


Fig. 8. Freezes vs. Video resolution.

analysis, most of these spikes are caused by the packet loss and packet retransmitting due to the variability of the wireless channels. It is observed that there is a few of jitter "spikes" in EcoMD, which also verifies the reliability of video delivery.

(4) Playback freeze: Playback freeze is considered as a metric for evaluating the playback continuity. We compute the playback freeze frequency by recording the number of times when the playback buffer is empty during the playback process in this experiment. Three different resolutions of videos can be considered and compared. Fig. 8 plots the comparison results when EcoMD, QUVoD and VMesh are used in turn when increasing video resolutions. In this experiment, the mobility speed is fixed at 40 km/h and the system scale is set to 200 vehicular nodes. As the figure shows, the frequency of playback freeze in VMesh is much higher than any of other solutions, especially in a high video resolution. That is because the delivery path employed in VMesh suffers high packet loss rate when the resolution are at high levels. The EcoMD performs better than QUVoD by about 10%. It is mainly because the adaptive path selection and providers maintaining which provide a high level of multimedia delivery based on the users' requirements (i.e. video resolution).

We further study the frequency of playback freeze for different moving speeds. The moving speed is also ranging from 20 km/h to 60 km/h. The resolution of videos is 4CIF. Fig. 9 shows the comparison results. When nodes have low moving speeds (less than 30 km/h), all solutions perform fairly well with the similar performance (between 0.13 and 0.17). However, the VMesh performance decreases obviously with the increase of moving speeds, the playback freezes reach to 0.37 when the speed is up to 60 km/h. In EcoMD, the frequency of playback freeze is maintained at a low level, with 12–40% lower than that of VMesh and 6–20% lower than that of QUVoD. The main reasons are as follows. The data transmitted in VMesh is not reliable in high speed mobile circumstances. QUVoD and EcoMD make use of the 4G/LTE as a solution to guarantee the users' QoE. Besides, the caching enhancement mechanism used in EcoMD also improves the playback continuity.

(5) User QoE estimation: We analyze video user QoE estimation in terms of PSNR, VQM, SSIM and MOS. The average PSNR of the sent video is 99dB, which represents the case of no distortions in any frame of the video. Fig. 10 presents the QoE reference score of average video quality, expressed in terms of PSNR (dB), SSIM VQM and MOS. VQM is a video quality evaluation metric, which is based on a simplified human spatial-temporal contrast sensitivity model. As the Fig. 10(a) shows, EcoMD has a better performance than both VMesh and QUVoD. For example, when vehicle speed is 20 km/h, the average PSNR of VMesh and QUVoD are about 26.45 and 34.62, respectively, and the PSNR of EcoMD is 46.48, achieving an improvement of 34%–75%. However, when the speed reaches 60 km/h, the PSNR of VMesh drops to 10.46, while that of the QUVoD is 20.63. EcoMD's remains as high as 38.49. This can be explained by the benefits of using the information-centric solutions which help users get better suppliers and delivery paths based on the QoE requirements.

Similar results are presented in terms of SSIM and VQM (Fig. 10(b) and (c)). Based on these results, we further analyze the subjective evaluation for EcoMD in terms of MOS. We employ a five-level MOS scale (i.e. 1-bad, 2-poor, 3-fair, 4-good, 5-excellent) for MOS-based user quality of experience evaluation. Seven volunteers have evaluated subjectively different video samples, which are collected following the employment of various simulation solutions. These volunteers have watched the video clips on a laptop, and then have given MOS scores for the watched videos. To reduce the effect of random errors, all the test subjects were required to first study an article about QoS-QoE correlation for their information. Each volunteer has watched video clips delivered over network with the three different transmission solutions, used in turn: EcoMD, VMesh and QUVoD. For each transmission solution employed, we have collected the results, have removed the highest and lowest scores as outliers and then have computed the average score as the final MOS value.

Fig. 10(d) shows how EcoMD has the highest MOS among three solutions tested, confirming that EcoMD outperforms VMesh and QUVoD in terms of QoE scores. In this figure, the MOS values of VMesh and QUVoD decrease when vehicle's average speed increases. For instance when VMesh is employed and the speed reaches 60 km/h, the performance becomes very poor, as the associated MOS reduces to 2, value unacceptable for any user. When

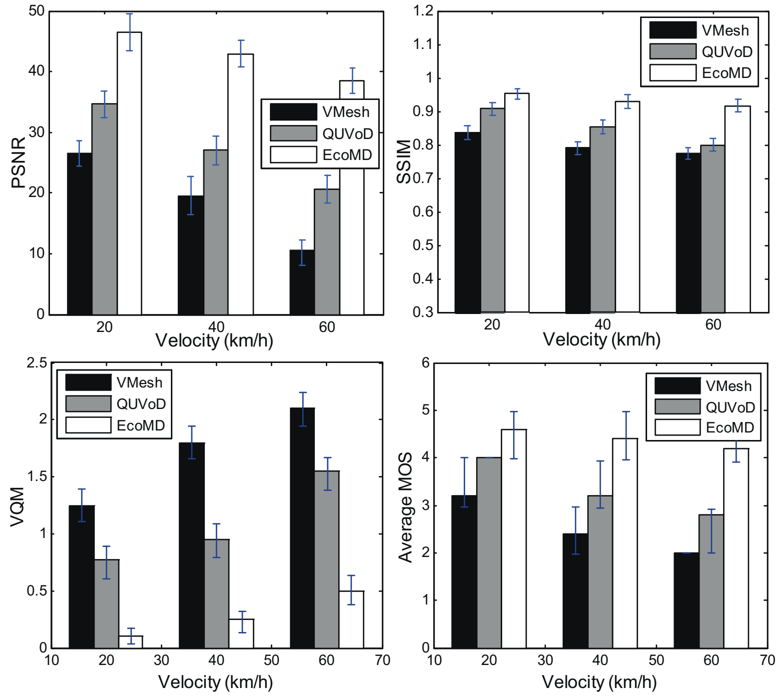


Fig. 10. Comparison of user QoE estimation: (a) PSNR (b) SSIM (c) VQM (d) MOS.

QUVoD is used in turn, the resulting MOS decreases to 3 when the speed reaches 60 km/h. The main reason for this MOS decrease is that the solutions find a stable content supplier with increasing difficulty in highly mobile circumstances. When EcoMD is employed, MOS is kept at a high level even when the speed reaches 60 km/h. This is due to the in-path caching enhancement which increases the number of potential content providers, alleviating the negative effect of high speed.

In order to comparatively illustrate the user QoE estimation results, we have selected many snapshots directly taken from the received video when the three solutions are used in turn. The results are shown in Fig. 11. For each solution, multiple snapshots in different frames are also collected and compared. Fig. 11(a), (b) and (c) denote the snapshots received by EcoMD, QUVoD and VMesh, respectively. It can be observed that EcoMD's snapshots are at the highest quality level. The main reason is that the EcoMD employs the proposed adaptive mechanisms including path selection, source maintaining and in-path caching to enhance users' QoE. The VMesh performs the worst due to the unstable connectivity of VANETs. QUVoD has obtained a result between EcoMD and VMesh. The figures clearly illustrate EcoMD outperforms the other solutions in terms of perceptual quality of video.

(6) Cost-efficiency-related metrics: Finally, we analyze the main cost-efficiency-related metrics in terms of system control overhead, cost efficiency and utilization of different delivery paths. We consider that a high system control overhead may result in an extra cost for users. Also, the frequency of using different delivery paths will affect the total cost greatly. For example, it has a high cost to use the expensive delivery paths greedily, even for videos with low quality. The results are analyzed as follows.

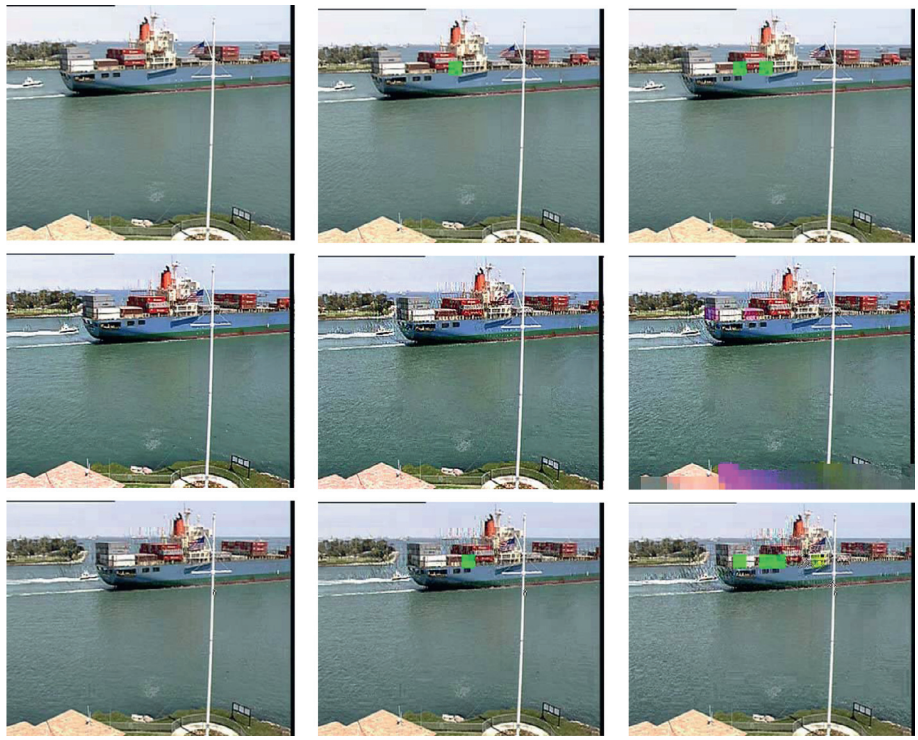
(i) Control overhead: We define the control overhead as the bandwidth used for control message exchange per second, which can be calculated according to the trace log. In Fig. 12, we observe that the control overhead increases with the number of vehicles, because the increase in system scale will increase the number of exchanged control messages. We also notice that the growth rate decreases as the number of vehicles grows. That is because as the density of vehicles increases, more and more relatively steady

Table 6
Three adopted price strategies.

Strategies	V2V	V2R	V2I
Strategy A	1 unit	2 units	4 units
Strategy B	1 unit	2 units	3 units
Strategy C	1.3 units	2 units	2.3 units

and reliable resource peers to be used, which can avoid frequent control operations. VMesh performs the worst because the overlay on top of VANETs is easily affected by the underlying vehicles' mobility, and each vehicle needs frequent exchange of messages to maintain the real-time connections and nodes' frequently joining and leaving. Different from VMesh, QUVoD introduces a Chord overlay strategy on the top of a 4G network, which is robust to variable network conditions. However, the cost of maintaining the Chord architecture needs a certain control overhead. In EcoMD, the control overhead is less than both two. The main reason is that EcoMD adopts the information-centric forwarding architecture, which is a natural distributed control system with less control messages because of the following two reasons. First, it removes the connection-based communication, hence reduces the maintainance of long host-to-host connections. Second, some necessary control information can be easily embedded in inherent *Interest* or *Data* packets.

(ii) Economic cost: Due to the different economical costs in different paths, the probability of using paths will reflect economic cost of the system. We further make an investigation for costs efficiency for the three solutions. To minimize the loss of generality, we select three representative price strategies, which are listed in Table 6. It is noted that these price strategies mainly reflect the different increasing complexity in V2V, V2R and V2I paths. The strategy A adopts an exponential growth rate, the strategy B uses a linear growth rate and the strategy C selects a logarithmic growth rate. Fig. 13 shows the costs of the three solutions based on different price strategies. We observe the VMesh has the least economic cost. It is easily understood that only one path is used in VMesh



(a) EcoMD (b) QUVoD (c) VMesh

Fig. 11. The comparison of different frames taken from received and reconstructed videos by three solutions.

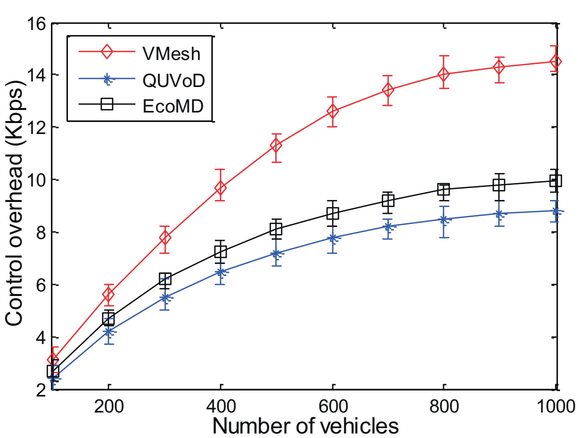


Fig. 12. Control overhead vs. Number of vehicles.

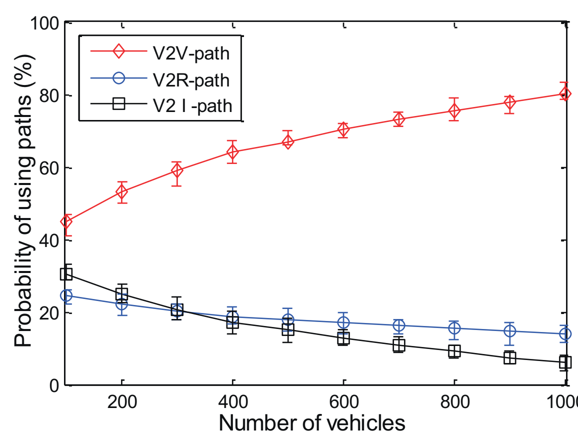


Fig. 14. Utilization of three different paths.

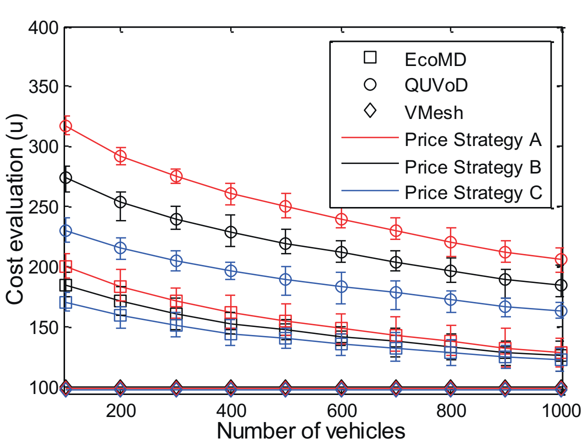


Fig. 13. Economical costs on price strategies.

which makes the cost independent on the price strategy. However, we note that VMesh provides an relatively poor service level based on the above analysis, which means it worthless despite a low cost. EcoMD has a lower economical cost than QUVoD, and has lower variation in the three price strategies. This means EcoMD is less dependent on the high cost path, and reduces the effect of different price strategies. The main reason is that the three economical mechanisms employed in EcoMD is able to adjust the utilization of paths on demand.

(iii) Utilization of paths: The utilization of paths is analyzed as follows. In this experiment, the probability of using each path is measured by the average ratio of the request response number via each path and the total number of requests. This information can be calculated from the requests trace file. We focus on the probability against the increase of the number of vehicular nodes. Fig. 14 illustrates the results of the investigation on the average probability of using V2V, V2R and V2I paths to retrieve video segments in EcoMD. In this figure, the utilization of V2V path increases as the increase of system scale, while those of V2R and V2I decrease. When there are fewer vehicular nodes, for instance, the number is 100, the probability of using V2I path is around 30%, the V2R path is used with probability of 25%, and there is about 45% chance of using the V2V path. However, with the increase in the system scale, the probability of using V2V path has increased significantly.

7. Conclusion

This paper has introduced EcoMD, a novel information-centric cost-efficient multimedia delivery solution for VANETs. Adaptive heuristic mechanisms are proposed to achieve a cost-efficient video delivery in three stages: (i) priority-based path selection, (ii) least-required sources maintaining and (iii) on-demand caching enhancement. Simulations results have shown how EcoMD provides great benefits in terms of start-up delay, playback continuity, jitter, overhead, user perceived quality and economic cost at acceptable quality level in comparison with two state-of-the-art alternative solutions. We believe this work has a great potential to support high quality multimedia applications in ubiquitous networking environments, addressing users' increasing demand. Future work will consider optimal video content distribution in order to further improve EcoMD's performance. Additionally, energy consumption will also be studied to build green multimedia streaming solutions.

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References

[1] Cisco, Cisco visual networking index: Forecast and methodology, White Paper, 2014.
[2] C. Xu, S. Jia, L. Zhong, G.-M. Muntean, Socially aware mobile peer-to-peer communications for community multimedia streaming services, IEEE Commun. Mag. 53 (10) (2015) 150–156, doi:10.1109/MCOM.2015.7295477.
[3] X. Jiang, D. Du, Bus-vanet: A bus vehicular network integrated with traffic infrastructure, IEEE Intell. Transp. Syst. Mag. 7 (2) (2015) 47–57, doi:10.1109/MITS.2015.2408137.
[4] C. Xu, S. Jia, M. Wang, L. Zhong, G.-M. Muntean, Performance-aware mobile community-based vod streaming over vehicular ad hoc networks, IEEE Trans. Vehic. Technol. 64 (3) (2015) 1201–1217, doi:10.1109/TVT.2014.2329696.
[5] B. Alessandro, B.M. Masini, G. Pasolini, Real time acquisition of traffic information through v2v, v2r, and v2i communications, Chapter in Roadside Netw. Vehic. Commun. 2013 (4) (2013) 72–92, doi:10.4018/978-1-4666-2223-4.ch004.
[6] J. Dias, J.J.P.C. Rodrigues, N. Kumar, K. Saleem, Cooperation strategies for vehicular delay-tolerant networks, IEEE Commun. Mag. 53 (12) (2015) 88–94, doi:10.1109/MCOM.2015.7355571.
[7] T. Darwish, K.A. Bakar, Lightweight intersection-based traffic aware routing in urban vehicular networks, Comput. Commun. 87 (2016) 60–75. http://dx.doi.org/10.1016/j.comcom.2016.04.008.
[8] C. Xu, F. Zhao, J. Guan, H. Zhang, G.-M. Muntean, Qoe-driven user-centric vod services in urban multihomed p2p-based vehicular networks, IEEE Trans. Vehic. Technol. 62 (2013) 2273–2289, doi:10.1109/TVT.2012.2228682.
[9] N. Kumar, J.J.P.C. Rodrigues, S. Zeadally, Qos-aware hierarchical web caching scheme for online video streaming applications in internet-based vehicular ad hoc networks, IEEE Trans. Ind. Electron. 62 (12) (2015a) 7892–7900, doi:10.1109/TIE.2015.2425364.
[10] N. Kumar, J. Lee, J.J.P.C. Rodrigues, Intelligent mobile video surveillance system as a bayesian coalition game in vehicular sensor networks: Learning automata approach, IEEE Trans. Intell. Transp. Syst. 16 (3) (2015b) 1148–1161, doi:10.1109/TITS.2014.2354372.
[11] L. Zhou, Z. Yang, J.J.P.C. Rodrigues, M. Guizani, Exploring blind online scheduling for mobile cloud multimedia services, IEEE Wireless Commun. Mag. 20 (3) (2013) 54–61, doi:10.1109/MWC.2013.6549283.
[12] H. Zhang, P. Dong, W. Quan, B. Hu, Promoting efficient communications for high-speed railway using smart collaborative networking, IEEE Wireless Commun. 22 (6) (2015) 92–97, doi:10.1109/MWC.2015.7368829.
[13] H. Zhang, W. Quan, H. Chao, C. Qiao, Smart identifier network: A collaborative architecture for the future internet, IEEE Netw. 30 (3) (2016) 46–51, doi:10.1109/MNET.2016.7474343.
[14] B. Ahlgren, C. Dannewitz, C. Imbrenda, D. Kutscher, B. Ohlman, A survey of information-centric networking, IEEE Commun. Mag. 50 (2012) 26–36, doi:10.1109/MCOM.2012.6231276.
[15] V. Jacobson, D.-K. Smetters, Networking named content, Commun. ACM 51 (2012) 117–124, doi:10.1145/1658939.1658941.
[16] D. Trossen, G. Parisis, Designing and realizing an information-centric internet, IEEE Commun. Mag. 50 (2012) 60–67, doi:10.1109/MCOM.2012.6231280.
[17] M. Amadeo, O. Briante, C. Campolo, A. Molinaro, G. Ruggeri, Information-centric networking for {M2M} communications: Design and deployment, Comput. Commun. (2016). http://dx.doi.org/10.1016/j.comcom.2016.03.009. –
[18] W. Quan, C. Xu, J. Guan, H. Zhang, L.A. Grieco, Scalable name lookup with adaptive prefix bloom filter for named data networking, IEEE Commun. Lett. 18 (2014) 102–105, doi:10.1109/LCOMM.2013.112413.132231.
[19] W. Quan, J. Guan, C. Xu, S. Jia, J. Zhu, H. Zhang, Content retrieval model for information-centric manets: 2-dimensional case, Proc. IEEE WCNC 2013 (2013) 4422–4427, doi:10.1109/WCNC.2013.6555290.
[20] W. Quan, J. Guan, S. Jia, J. Zhu, C. Xu, H. Zhang, A content retrieval model for information centric manets: 1-dimensional case, Proc. IEEE GLOBECOM 2012 (2012) 1010–1015, doi:10.1109/GLOCOMW.2012.6477715.
[21] C. Xu, J. Zhao, G.-M. Muntean, Congestion control design for multipath transport protocols: A survey, IEEE Commun. Surv. Tut. PP (2016) 1–22, doi:10.1109/COMST.2016.2558818.
[22] C. Xu, T. Liu, J. Guan, H. Zhang, G.-M. Muntean, Cmt-qa: Quality-aware adaptive concurrent multipath data transfer in heterogeneous wireless networks, IEEE Trans. Mob. Comput. 12 (2013) 2193–2205, doi:10.1109/TMC.2012.189.
[23] C. Xu, Z. Li, J. Li, H. Zhang, G.-M. Muntean, Cross-layer fairness-driven concurrent multipath video delivery over heterogenous wireless networks, IEEE Trans. Circuits Syst. Video Technol. 25 (2015) 1175–1189, doi:10.1109/TCSVT.2014.2376138.
[24] F. Naeimipoor, A. Boukerche, A hybrid video dissemination protocol for vanets, IEEE Trans. Vehic. Technol. 62 (2013) 2273–2289, doi:10.1109/TVT.2012.2228682.
[25] M. Asefi, J.W. Mark, X. Shen, A mobility-aware and quality-driven retransmission limit adaptation scheme for video streaming over vanets, IEEE Trans. Wireless Commun. 11 (2012) 1817–1827, doi:10.1109/TWC.2012.030812.111064.
[26] C. Rezende, A. Mammeri, A. Boukerche, A.F. Loureiro, A receiver-based video dissemination solution for vehicular networks with content transmissions decoupled from relay node selection, Ad Hoc Netw. 17 (2014a) 1–17, doi:10.1016/j.adhoc.2013.12.011.
[27] C. Rezende, A. Boukerche, H. Ramos, A reactive and scalable unicast solution for video streaming over vanets, IEEE Trans. Comput. 64 (2014b) 614–626, doi:10.1109/TC.2014.2308176.
[28] L. Zhou, Y. Zhang, K. Song, W. Jing, A.-V. Vasilakos, Distributed media services in p2p-based vehicular networks, IEEE Trans. Vehic. Technol. 60 (2011) 692–703, doi:10.1109/TVT.2010.2102782.
[29] A. Detti, B. Ricci, N. Blefari-Melazzi, Mobile peer-to-peer video streaming over information-centric networks, Comput. Netw. 81 (2015) 272–288, doi:10.1016/j.comnet.2015.02.018.
[30] S. Lederer, C. Mueller, C. Timmerer, H. Hellwagner, Adaptive multimedia streaming in information-centric networks, IEEE Netw. 28 (2014) 91–96, doi:10.1109/MNET.2014.6963810.
[31] G. Piro, L.A. Grieco, G. Boggia, P. Chatzimisios, Information-centric networking and multimedia services: present and future challenges, Trans. Emerg. Tel. Tech. 25 (2013) 1–15, doi:10.1002/ett.2741.
[32] Z. Zhu, S. Wang, X. Yang, Act: Audio conference tool over named data networking, Proc. ACM SIGCOMM Workshop ICN 2011 (2011) 68–73, doi:10.1145/2018584.2018601.
[33] L. Han, S.S. Kang, H. Kim, Adaptive retransmission scheme for video streaming over content-centric wireless networks, IEEE Commun. Lett. 17 (2013) 1292–1295, doi:10.1109/LCOMM.2013.043013.130326.
[34] Y. Liu, J. Geurts, J.C. Point, Dynamic adaptive streaming over ccn: A caching and overhead analysis, Proc. of IEEE ICC 2013 (2013) 3629–3633, doi:10.1109/ICC.2013.6655116.
[35] Z. Li, M.-K. Sbar, Network friendly video distribution, Proc. Int. Conf. Netw. Future 2012 (2012) 1–8, doi:10.1109/NOF.2012.6463984.
[36] A. Detti, M. Pomposini, N.B. Melazzi, S. Salsano, Offloading cellular networks with information-centric networking: The case of video streaming, Proc. IEEE WoWMoM 2012 (2012) 1–3, doi:10.1109/WoWMoM.2012.6263734.
[37] Z. Li, G. Simon, Time-shifted tv in content centric networks: the case for cooperative in-network caching, Proc. IEEE ICC 2011 (2011) 1–6, doi:10.1109/icc.2011.5963380.
[38] M. Amadeo, C. Campolo, A. Molinaro, Content-centric networking: Is that a solution for upcoming vehicular networks, Proc. ACM Int. Workshop VANET 2012 (2012) 99–102, doi:10.1145/2307888.2307906.
[39] L. Wang, R. Wakikawa, R. Kuntz, Data naming in vehicle-to-vehicle communications, Proc. IEEE INFOCOM workshop 2012 (2012) 328–333, doi:10.1109/INFCOMW.2012.6193515.
[40] G. Arnould, D. Khadraoui, Z. Habbas, A self-organizing content centric network model for hybrid vehicular ad-hoc networks, Proc. ACM DIVANet 2011 (2011) 15–22, doi:10.1145/2069000.2069004.
[41] P. TalebiFard, V. Leung, A content centric approach to dissemination of information in vehicular networks, Proc. ACM DIVANet 2012 (2012) 17–24, doi:10.1145/2386958.2386962.

[42] S. Bouk, S. Ahmed, D. Kim, Hierarchical and hash based naming with compact trie name management scheme for vehicular content centric networks, Comput. Commun. 71 (2015) 73–83, doi:10.1016/j.comcom.2015.09.014.
[43] R. Wakikawa, R. Vuyyuru, Ndn applicability to v2v and v2r networks, 2012, (CCNxCon2012, http://www.ccnx.org/ccnxcon2012/talks/).
[44] I.D. Baev, R. Rajaraman, C. Swamy, Approximation algorithms for data placement problems, SIAM. J. Comput. 38 (2008) 1411–1429, doi:10.1137/080715421.
[45] S. Jia, C. Xu, J. Guan, H. Zhang, G.-M. Muntean, A novel cooperative content fetching-based strategy to increase the quality of video delivery to mobile users in wireless networks, IEEE Trans. Broadcasting 60 (2014) 370–384, doi:10.1109/TBC.2014.2322772.
[46] Y. He, G. Shen, Y. Xiong, L. Guan, Optimal prefetching scheme in p2p vod applications with guided seeks, IEEE Trans. Multimedia 11 (2009) 138–151, doi:10.1109/TMM.2008.2008929.
[47] ndnsim, 2013, (http://ndnsim.net/intro.html).
[48] Vanetmobisim, 2015, (http://vanet.eurecom.fr).
[49] Ns3-qoe monitor, 2014, (http://sourceforge.net/projects/ns3qoemonitor).
[50] A. Brampton, A. MacQuire, I. Rai, Characterizing user interactivity for sports video-on-demand, in: Proceedings of ACM NOSSDAV, 2007, doi:10.1145/2713168.2713183.
[51] Xiph-org video test media, 2014, (http://media.xiph.org/video/derf).
[52] Aone-soft, 2014, (http://www.aone-soft.com/splitter.htm).
[53] S.-H. G. Chan, W.-P. K. Yiu, Distributed storage to support user interactivity in peer-to-peer video, US Patent, 2011. doi: USPatent/7925781
[54] D. Niyato, E. Hossain, Dynamics of network selection in heterogeneous wireless networks: An evolutionary game approach, IEEE Trans. Vehic. Technol. 58 (2009) 2008–2017, doi:10.1109/TVT.2008.2004558.