IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received June 2, 2020, accepted June 18, 2020, date of publication June 23, 2020, date of current version July 6, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3004228

A Bandwidth-Aware Video Segments Request Strategy to Optimize User's QoE in Connected Vehicle Networks

JUZHENG DUAN[1], KUN LI[1,2], YUN HE[1], MIN ZHANG[1], AND XIAOLONG YANG[1], (Member, IEEE)

[1]School of Computer and Communication Engineering, University of Science and Technology Beijing, Beijing 100083, China
[2]Beijing Institute of Aerospace Control Devices, Beijing 100094, China

Corresponding author: Min Zhang (zhangm@ustb.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671057 and Grant 61941113.

ABSTRACT In ITS environment, the driver-assistant services usually demand delivering video content to vehicular users, which is very useful in the intervention of emergency services, and reminds the drivers the traffic jam in ahead road. Nowadays for online video delivery in connected vehicle networks, HTTP adaptive streaming (HAS) is one of the most promising technologies, where a video is encoded into multiple bitrates and then split into small segments. It is crux for ITS service providers how to improve users' QoE through an adaptive video segments request strategy. From the perspective of adaptive matching among segment bitrate, network bandwidth, and buffer occupancy, we propose a bandwidth-aware video segment request strategy to optimize user's QoE (for short Bw-QoE), which consists of two parts, i.e., available bandwidth estimation, and segment's bitrate selection. First, based on the severity of bandwidth fluctuation, Bw-QoE estimates the available bandwidth with different historical weighted average methods. Then constrained by the estimated available bandwidth and buffer occupancy, the adaptive bitrate selection is formulated as an optimization model to maximize user's QoE of a video streaming session. It is fairly attractive for Bw-QoE to prevent buffer overflow, underflow and unuseful download, and to reduce bitrate switching. Compared with the classic strategy (e.g., LIU's strategy), the simulation results show that the proposed strategy Bw-QoE has higher average video bitrate (about 8%-10%), less interruption (about 100%), less segment bitrate switching (about 15%-17%) and higher buffer occupancy (about 13%-51%), which demonstrate that our strategy effectively improves QoE.

INDEX TERMS Adaptive request strategy, connected vehicle network, HTTP adaptive streaming (HAS), intelligent transport systems (ITS), quality of experience (QoE).

I. INTRODUCTION

With the increasing vehicles equipped with mobile communication devices and in-vehicle multimedia entertainment systems, Intelligent Transport Systems (ITS) have been widely deployed to enable diverse driver-assistant services related to road safety, traffic efficiency, and infotainment [1]. In ITS environment, the driver-assistant services usually demand delivering video content to vehicular users, which includes video clips of an accident or a critical situation (e.g. traffic congestion, fire, flood, terrorist attack) occurring on a highway [2]. In practice, the real-time reliable delivery of video about accidents is very useful in the intervention of emergency services, and reminds the drivers to predict the duration of the traffic jam in various areas.

Besides its increasing attractiveness for ITS applications, video streaming is becoming one of the most popular Internet applications. Known from Cisco visual networking index, the global video traffic volume is estimated to reach 32EB per month by 2021, and to account for 78% of the entire Internet traffic [3]. However, it is a greatly challenging task for delivering video content in the vehicular networks due to the high mobility of the vehicles and network instability and scalability.

As usual, user's entertainment and driver-assistant information services require the reception of multimedia data

The associate editor coordinating the review of this manuscript and approving it for publication was Amr Tolba.

in an acceptable quality. However, when the vehicle moves through the areas of deep fading/low signal, and enters or departs the congested areas in rapid succession, its high driving speed would cause the wireless channel conditions changing rapidly. In addition, the Doppler effects imposed by its high-speed movement may disturb video streaming under the wireless environment. Besides, the quick handovers with its increasing speed should make the interruption of the service. Hence actually, the high mobility of the vehicle is a severe obstacle to the reliable video streaming of ITS and the Quality of Experience (QoE) of vehicular users [4]. Besides the mentioned problems incurred by the high mobility of the vehicles, the network instability and scalability inherent in connected vehicle networks have great side-effects on streaming-type driver-assistant services. Additionally, some socio-economic issues have also great influences on the in-vehicle multimedia value-added services, which include the cost of infrastructure needed for the deployment of connected vehicle solutions and the market penetration of car-to-car and car-to-infrastructure communication technologies.

In fact, the end-to-end bandwidth of path in connected vehicle networks is time-varying due to many factors, e.g., vehicle high-speed mobility, wireless channel attenuation, and radio interference. The time-variant bandwidth of path affects video distribution directly, and further makes influences on playback [5]. In addition, there are a variety of heterogeneous in-vehicle terminals with different performance and resolution. Because of the reasons above, user's viewing experience is influenced by in-bound/out-bound bandwidth of connected vehicle networks and in-vehicle terminal performance. Therefore, how to deliver the video content with different bitrates to enhance user's QoE is an important concern for ITS service providers under the connected vehicle networks environment [6].

Nowadays for online video delivery in ITS situations, there are only a few approaches proposed for vehicular network. HTTP adaptive streaming (HAS) is one of the most promising video distribution technologies, and is widely deployed in many famous video streaming service providers (e.g., YouTube, Youku) [7]. In HAS, a video is encoded into multiple bitrates, and is split into small segments in the source. In the client side, a user adaptively requests the next segment with an appropriate bitrate constrained by current network condition and buffer occupancy [8]. Compared with non-adaptive methods, HAS effectively reduces stalling about 80% and increases greatly the utilization of the available bandwidth [9]. Up to now, HAS has become one of widely used de facto standards due to its unique adaptation features that allows the users to stream video using a bit rate closely matching the available bandwidth from the server to the client, and also allows dynamic selection of quality representations in the face of network fluctuation.

According to the difference of reference information in decision-making, the existing adaptive request strategies of video distribution in HAS can be roughly classified into two types, i.e., bandwidth-based strategies and buffer-based strategies.

As usual, the bandwidth-based ones adaptively make a decision to select an appropriate bitrate for the next segment based on the estimation of bandwidth. Thang *et al.* [10] makes a decision to select the bitrate of the next segment based on Logistic function, which estimates the available bandwidth of the next moment. Liu *et al.* [11] proposed an adaptive strategy according to the ratio of media segment duration (MSD) to segment fetch time (SFT), which reflects the fluctuation trend of available bandwidth. These strategies effectively achieve a smooth switching of segment bitrates during a video streaming session. However, in real networks, the end-to-end bandwidth of path may have fast and drastic fluctuations, which further affect the accuracy of estimated bandwidth. In this case, a large number of segments need to be downloaded in buffer to counteract the adverse impact caused by bandwidth fluctuations.

There are some limitations in adaptive request strategies which only rely on the estimated bandwidth, therefore buffer-based strategies come into being, e.g., [12]–[14]. Buffer can counteract the fluctuations of available bandwidth to a certain extent, and maintain a smooth playback in the client. The common idea of buffer-based strategies is to divide the buffer into several zones by thresholds, and different actions will be taken when the buffer occupancy stays in different zones. In [12], the buffer is divided into four buffering zones which are corresponding to four different selection rules to choose the appropriate bitrate of the next segment. Raca *et al.* [13] proposed an adaptive request strategy based on buffer occupancy of the next moment. Its advantage is that it can reduce the negative impact caused by bitrate variations, prevent buffer underflow, and then achieve a balance between high-quality video and stable buffer state. In [14], MASH constructs probabilistic view switching models that capture the switching behavior, and then uses a new buffer-based approach to request video segments of various views at different qualities, such that the quality of the streamed videos is maximized while the network bandwidth is not wasted. Although the performance of buffer-based strategy is sensitive to the change of buffer occupancy, it can maintain the buffer occupancy in an appropriate zone, which effectively avoids the buffer underflow and overflow. However, if the fluctuation of network bandwidth lasts for a long time, the resulting frequent bitrate switching will inevitably worsen user's experience.

Although the existing video adaptive request strategies can improve the user's viewing experience to a certain extent, they do not consider the adaptive matching between network bandwidth, buffer occupancy, and segment bitrate from the perspective of quality of experience (QoE). Quality of Experience (QoE) is a concept of subjectively perceived quality and guarantees all customers to have a good service [15]. Constrained by buffer occupancy, we propose a bandwidth-aware segment request strategy to optimize user's QoE (for short Bw-QoE). At present, QoE can be

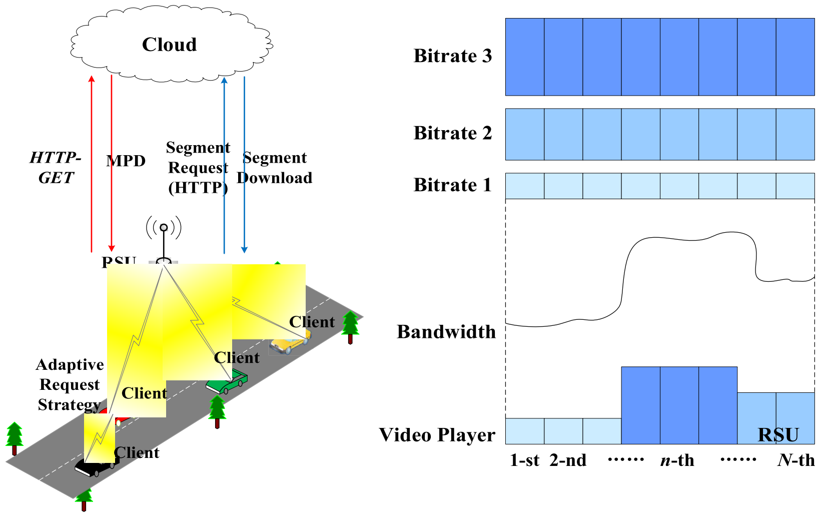


FIGURE 1. HTTP adaptive streaming system architecture for connected vehicle networks.

evaluated by subjective and objective methods. The MOS (Mean Opinion Score) proposed in ITU-T P.800 is a classic subjective method, which calculates MOS by artificially scoring of the viewing [16]. This method is highly subjective and requires a large number of ordinary users who have no contact with relevant business. For this reason, we adopt objective method from perceptual factors and technical factors to evaluate QoE during a video streaming session. The perceptual factors which are directly perceived by end viewers include video quality, playback interruptions, and quality transitions. And the technical factor includes playback buffer occupancy. Compared with the classic strategy, Bw-QoE can always select the most appropriate bitrate for requesting the video segment, fairly decrease the segment switching, and finally effectively optimize QoE for users.

The rest of the paper is organized as follows. Section 2 details how to design the strategy Bw-QoE for high-speed connected vehicle networks, which is subdivided into two problems, i.e., the available bandwidth estimation under different bandwidth fluctuation severity, and the bitrate selection jointly constrained by the available bandwidth and buffer occupancy. Then, section 3 presents some simulations to evaluate the performance of Bw-QoE, and compares it with a classic strategy (LIU's strategy in [8]) from many aspects, including the average video bitrate, the number of interruptions, the number of segment bitrate switching and the average buffer occupancy. Finally, section 4 draws a conclusion.

II. THE DESIGN OF BANDWIDTH-AWARE SEGMENT REQUEST STRATEGY

A. SYSTEM MODEL

In HTTP adaptive streaming as shown by Fig.1, a video in server is encoded into m bitrate versions. Each video is split into N segments with the same length of T seconds. The segment with higher bitrate has larger resolution and data size. During the video distribution, first client sends HTTP-GET to server to obtain MPD (Media Presentation Description), which is an index file and includes the related information of all the segments of a video. After receiving the MPD from server, client parses MPD and makes a decision to request a segment with an optimal bitrate. For example, if the available bandwidth is in a high level, and the buffer is in an appropriate state when the client requests the n-th segment, so the adaptive strategy in client requests the n-th segment with high bitrate. Once receiving the corresponding segment from server, client decodes and plays it [17], [18].

In fact, segment request strategy has a much greater impact on user's quality of viewing experience (i.e., QoE). In order to improve user's QoE, its design must consider the following requirements [19]. First, the strategy requests some appropriate segments to avoid interruption during the playback. Second as far as possible, it requests a segment with higher bitrate to make full use of the available bandwidth. Besides, it remarkably reduces the segment bitrate switching during a video streaming session. Hence, we propose a Bw-QoE strategy to select the most appropriate segment under the constraints of bandwidth and buffer, which optimize user's QoE. In order to realize the optimization goal of this strategy, we subdivide it into two following problems. (1) Bandwidth estimation. According to the severity of bandwidth fluctuation in end-to-end bandwidth of path, the client estimates the available bandwidth $\widehat{bw}$ for the next segment by different methods. (2) Bitrate selection. After the successful delivery of the $(n-1)$-th segment, the client requests the n-th segment with bitrate r_n to optimize user's QoE based on the estimated bandwidth $\widehat{bw}$ and the buffer occupancy.

B. BANDWIDTH ESTIMATION ALGORITHM FOR CONNECTED VEHICLE NETWORKS

In order to maximize user's QoE, the request strategy must select an appropriate bitrate for each requesting segment, which should match the available bandwidth. Obviously, the estimation of available bandwidth plays an important role in the request strategy [20]. If the available bandwidth is overestimated, the strategy may select a bitrate much higher than the current available bandwidth, which makes the requesting segment not timely reach the client when the segment is just right the next-playing one, and further leads to playback interruption for users. On the contrary, if the available bandwidth is underestimated, the strategy may select a bitrate much lower than the current available bandwidth, which wastes network resources and cannot provide an optimal experience during the playback. Therefore, it's necessary to estimate the time-varying bandwidth as accurately as possible to ensure the best viewing QoE.

Considering the two cases of slight fluctuations and obvious variations in end-to-end bandwidth of path, we deal with them separately, and propose a new bandwidth estimation algorithm based on the severity of bandwidth fluctuation. The bandwidth estimation consists of two steps. The first one is to determine the severity of bandwidth fluctuation. Then according to the judgments of bandwidth fluctuation, the second one is to design different historical weighted average methods to estimate the bandwidth, respectively.

The severity of bandwidth fluctuation is determined as follows. Let $bw(n)$ and $bw(n)$ denote the real available bandwidth and the estimated available bandwidth when the n-th segment is successfully delivered. As usual, the available bandwidth at this time can be expressed by the delivery throughput of the n-th segment.

$$bw(n) = \frac{S(n)}{\Delta t(n)} \tag{1}$$

where $S(n)$ denotes the data size of the n-th video segment and $\Delta t(n)$ is its transmission time. For a path, its end-to-end bandwidth fluctuation can be regard as a random event. As proved by the results in [19], the fluctuating bandwidth is assumed to conform to a normal distribution, with the expectation μ and the standard deviation σ. The empirical rule in [19] states that for any normal curve, 68% of the values fall within 1 standard deviation of the mean in either direction, so we choose $(\mu - \sigma, \mu + \sigma)$ as a prediction error interval to determine the severity of bandwidth fluctuation. If the estimated bandwidth $bw(n)$ is in this interval, the bandwidth slightly fluctuates around the mean value μ, and the available bandwidth is stable. In contrast, if $bw(n)$ is not in it, there is a large deviation between the estimated bandwidth and the real one. In a word, the bandwidth fluctuation is significantly severe.

Based on the fluctuation severity judgment, the bandwidth estimation can work as the following ways. For the case of slight bandwidth fluctuations, the bandwidth can be estimated by the weighted moving average method [20].

$$\widehat{bw(n+1)} = \sum\nolimits_{i=1}^{n} w_i bw(i) \tag{2}$$

where w_i denotes the weight of historical bandwidth and $\sum_{i=1}^{n} w_i = 1$. If the arriving time of a segment is closer to the current time, its weight should be larger. On the contrary, if the arriving time of a segment is further away from the current time, the segment weight should be smaller. The historical bandwidths of requested segments at distant past time cannot effectually reflect the bandwidth fluctuation trend, and are of no importance to estimate the current bandwidth. Hence, we can just consider the two most recent segments in bandwidth estimation as follows.

$$\widehat{bw(n+1)} = w_1 bw(n) + w_2 bw(n-1) + w_3 bw(n-2) \tag{3}$$

Based on Eq. (3), the short-term bandwidth fluctuations can be smoothed efficiently by the most recent historical segment bandwidths.

On the other hand, if the bandwidth fluctuation is severe, the estimation by Eq. (2) or Eq. (3) does not take effect, and brings large errors. Here, we do not consider all the previous bandwidth, and only use the current bandwidth to estimate the next-time one.

$$\widehat{bw(n+1)} = bw(n) \tag{4}$$

The above revised method can effectively reflect the instantaneous fluctuation trend of the real bandwidth, and improve the accuracy of bandwidth estimation.

C. BITRATE SELECTION ALGORITHM FOR CONNECTED VEHICLE NETWORKS

Based on the design requirements, the adaptive strategy should request each segment with a bitrate matching with the current available bandwidth. Actually, the constraint on bandwidth alone is not clearly enough to maximize user's QoE because buffer underflow and overflow may happen due to the limited buffer when the bitrate selection does not consider the buffer occupancy. Both of them may worsen user's QoE severely since buffer underflow causes playback interruptions while overflow results in bandwidth waste. So besides the current available bandwidth, the adaptive request strategy must take the buffer occupancy into account to avoid underflow and overflow. As shown by Fig. 2, in the client buffer B denotes the total buffer capacity with respect to time, B_{min} and B_{max} are the underflow threshold and the overflow threshold, respectively. Assumed that the $(n-1)$-th segment arrives at the buffer at the time t_{n-1}, and the buffer occupancy is $q(t_{n-1})$. Once requesting the n-th segment, we must make a decision to select an optimized bitrate r_n, which should not only fairly match the estimated bandwidth, but also meet the limitations of available buffering.

1) HOW TO AVOID BUFFER UNDERFLOW

The buffer occupancy decreases gradually along with the video playback. Once all of the buffering segments have been played, the buffer underflow occurs, which results in playing interruption. For purpose of ensuring a smooth playback, it is necessary to guarantee the next segment (i.e., the n-th segment) to completely arrive at buffer before the buffer

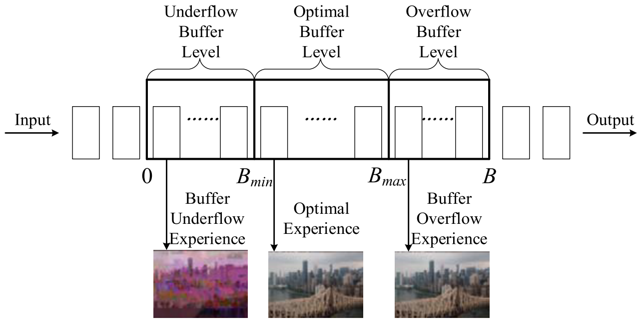


FIGURE 2. Client buffer.

occupancy is below B_{min}. This underflow constraint can be expressed as follows.

$$\int_{t_{n-1}}^{t_{n-1}+q(t_{n-1})-B_{\min}} \widehat{bw(t)dt} > r_n * T \tag{5}$$

where $\widehat{bw(t)}$ is the estimated bandwidth based on Eq. (3) or Eq. (4). Eq. (5) means that the data size transmitted in estimated bandwidth is larger than the segment with the selected bitrate r_n.

2) HOW TO AVOID BUFFER OVERFLOW

Similarly, the adaptive strategy also should prevent buffer overflow which results in bandwidth waste. Assumed that the n-th segment arrives at buffer at the time t_n, and the buffer occupancy is $q(t_n)$. Taking $q(t_{n-1})$ as a reference, $q(t_n)$ can be expressed as follows.

$$q(t_n) = q(t_{n-1}) + T - (t_n - t_{n-1}) \tag{6}$$

where T and $t_n - t_{n-1}$ are the length and transmission time of the n-th segment. Eq. (6) means that $q(t_n)$ increases T, and at the same time reduces $t_n - t_{n-1}$ due to video playback. After the n-th segment arrives at the buffer completely, $q(t_n)$ should be less than B_{max}. Hence, the overflow limitation can be expressed as follows.

$$q(t_n) = q(t_{n-1}) + T - (t_n - t_{n-1}) \leq B_{\max} \tag{7}$$

Meanwhile, in order to avoid the buffer underflow during the transmission of the n-th segment, the n-th segment should completely arrive before the buffer occupancy is below Bmin, which can be expressed as follows.

$$t_n - t_{n-1} \leq q(t_{n-1}) - B_{\min} \tag{8}$$

where $t_n - t_{n-1}$ is the transmission time of the n-th segment. According to Eq. (6)-(8), we can obtain the range of t_n. Then, we can select the bitrate r_n which meets overflow constrains based on the equation below.

$$\int_{t_{n-1}}^{t_n} \widehat{bw(t)dt} = r_n * T \tag{9}$$

3) HOW TO AVOID UNUSEFUL DOWNLOAD

During a video streaming session, it is possible that the current buffer occupancy $q(t_n)$ may exceed B_{max} even when the past one $q(t_{n-1})$ is less than B_{max}. Under this situation, the unuseful download for the n-th segment may occur if the data size of the n-th segment is larger than $\{B - q(t_{n-1}) - T + (t_n - t_{n-1})\}r_n$. Hence, in order to avoid unuseful download, $q(t_n)$ must less than the total length B, that is:

$$q(t_{n-1}) \leq B_{\max} \tag{10}$$

$$B_{\max} \leq q(t_{n-1}) + T - (t_n - t_{n-1}) \leq B \tag{11}$$

Based on Eq. (10) and Eq. (11), we can obtain the following equation.

$$T - (t_n - t_{n-1}) \leq B - B_{\max} \tag{12}$$

4) HOW TO SELECT THE MOST APPROPRIATE SEGMENT

In a video streaming session, the segment bitrate and the switching between different bitrates have great influences on user's QoE. As usual, higher segment bitrate and less switching amplitude result in better QoE for users. For simplicity, the relations between segment bitrate and QoE can be described as a linear equation (like the later Eq. (15)) while the relations between segment bitrate switching and QoE can be described as an exponential equation (like the later Eq. (16)). Hence, we define a QoE maximization function related to the two factors. The segment with bitrate r_n which maximizes the designed QoE function will be requested. For the n-th segment, the QoE maximization function is defined as follows.

$$\begin{aligned} \max[QoE]_n &= function(Bitrate\ gain,\ \text{Switching loss}) \\ &= p_1 g_1(r_n) + p_2 g_2(r_n) \end{aligned} \tag{13}$$

where $g_1(r_n)$ and $g_2(r_n)$ represent bitrate gain and switching loss. p_1 and p_2 denote the weight coefficients of gain and loss respectively. In addition, $p_1 + p_2 = 1$, and $p_1, p_2 \in (0, 1)$.

In a linear-like bitrate gain $g_1(r_n)$, there should be a large gain difference between the minimum bitrate and the maximize bitrate. In order to reduce the gain difference, we define μ_n as a normalized value to represent the bitrate gain brought by a segment with the selected bitrate r_n. μ_n can be expressed as

$$\mu_n = \frac{r_n}{r_{\max}} \tag{14}$$

where r_n is segment bitrate, $r_{\max}$ is the maximum bitrate of all the optional segments, and $\mu_n \in (0, 1]$. So $g_1(r_n)$ can be expressed as follows.

$$g_1(r_n) = \mu_n \tag{15}$$

In the loss part, larger switching amplitude causes much more loss, and we can simply use an exponential function to formulate the relation between the bitrate switching amplitude and the loss in QoE. Moreover, the downward switching ($r_n < r_{n-1}$) causes more loss than the upward switching ($r_n > r_{n-1}$) even if both of them have the same switching amplitudes. Because users cannot tolerate downward bitrate deterioration, we assign different coefficients a and b to upward switching and downward switching. $a + b = 1$, a,

$b \in (0, 1)$. We use a switching loss coefficient λ_n to represent the effect caused by bitrate switching.

$$\lambda'_n = \begin{cases} (1/a)^{|r_n - r_{n-1}|}, & r_n > r_{n-1} \quad (upward\ switching) \\ 0, & r_n = r_{n-1} \quad (keeping\ unchanged) \\ (1/b)^{|r_n - r_{n-1}|}, & r_n < r_{n-1} \quad (downward\ switching) \end{cases} \tag{16}$$

Equation (16) shows that there will be a large gap when the segment switching between different bitrates. In order to reduce the differences between multiple switching cases, and make them comparable, we make a min-max normalization on λ'_n to compress its amplitude, and get λ_n which is between 0 and 1.

$$\lambda_n = \frac{\lambda'_n - \min \lambda'_n}{\max \lambda'_n - \min \lambda'_n} \tag{17}$$

So switching loss $g_2(r_n)$ can be expressed as

$$g_2(r_n) = -\lambda_n \tag{18}$$

In addition, due to the memory decline, i.e., a psychology phenomenon for short-term memory, human have a deeper impression to initial part and end part of an event while having less impression to middle scene. Moreover, the impression of initial part is gradually weakening over time. The above phenomena are termed as "primacy effect" and "recency effect" in psychology [21]. Hence based on the psychology phenomena, the adaptive request strategy should take each segment in a video having different effect on QoE. According to the results in [21], the QoE effect intensity function $f(t)$ at time t is rewritten as follows.

$$f(t) = \frac{\alpha}{1+\alpha^2 t^2} + \frac{\beta}{1+\beta^2 (t-t_0)^2}, t \in [0, t_0] \tag{19}$$

where t_0 represents the total playing time of the video, α and β denote the factors of the "primacy effect" and the "recency effect", respectively. The i-th segment is lasting from $(i-1)T$ to iT in time, and its effect intensity can be expressed as

$$f_i = \int_{(i-1)T}^{iT} f(t)dt \tag{20}$$

Likewise, each segment of a video is assigned an effect intensity, all of which affect QoE collectively. If w_i is defined as the weight of the ith segment to QoE, and $\sum_{i=1}^{n} w_i = 1$, then w_i can be rewritten as follows.

$$w_i = \frac{f_i}{\sum_{i=1}^{n} f_i} \tag{21}$$

Based on the analysis about the effect intensity on QoE, we jointly consider the bitrate and the effect intensity of each segment in the bitrate gain part $g_1(r_n)$, which can be expressed as

$$g_1(r_n) = \sum_{i=1}^{n} w_i * \mu_i \tag{22}$$

Similarly, we jointly consider the bitrate switching and the effect intensity of all the segments in the loss part $g_2(r_n)$, which can be expressed as follows.

$$g_2(r_n) = -\sum_{i=1}^{n} w_i * \lambda_i \tag{23}$$

Based on the above analysis, the adaptive segment adaptation strategy can be formulated as a QoE optimization model under the constraints of bandwidth and buffer, which can be expressed as follows.

$$\max[QoE]_n = p_1 \sum_{i=1}^{n} w_i * \mu_i - p_2 \sum_{i=1}^{n} w_i * \lambda_i$$
$$s.t. \begin{cases} \int_{t_{n-1}}^{t_{n-1}+q(t_{n-1})-B_{\min}} \widehat{bw(t)}dt > r_n * T & (a) \\ q(t_n) = q(t_{n-1}) + T - (t_n - t_{n-1}) \le B_{\max} & (b) \\ t_n - t_{n-1} \le q(t_{n-1}) - B_{\min} & (c) \\ T - (t_n - t_{n-1}) \le B - B_{\max} & (d) \end{cases} \tag{24}$$

where Eq. (a) denotes the underflow constraint, and Eq. (b) and Eq. (c) jointly denote the overflow constraints. Eq. (d) denotes the unuseful download constraint. Based on the above model, the client can request the n-th segment with bitrate r_n that maximizes user's QoE.

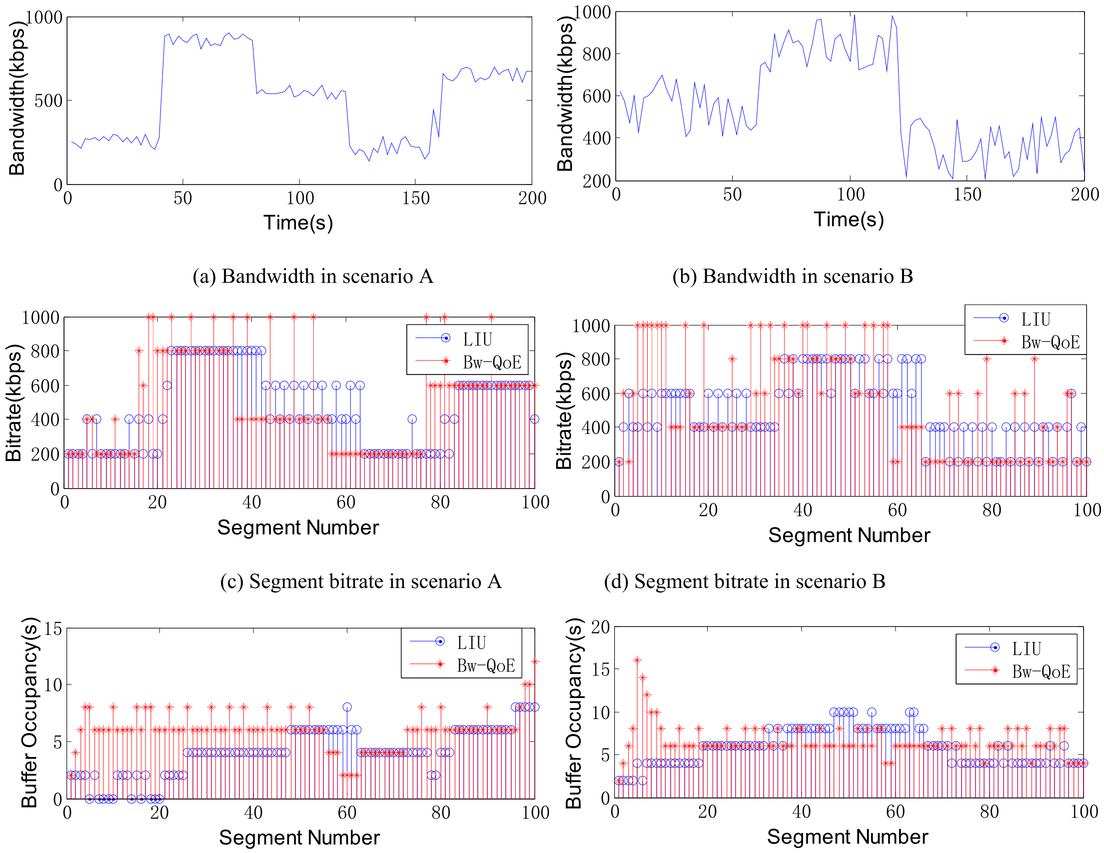
III. SIMULATION AND PERFORMANCE ANALYSIS

A. SIMULATION SCENARIOS SETUP

In order to comprehensively analyze the performance of the proposed strategy ***Bw-QoE***, we set up two simulation scenarios as follows. The first scenario A is a stable network environment where bandwidth fluctuations are relatively smooth. While the second scenario B is a variable network with severe bandwidth fluctuations. In our simulations, the number of video segments N is 100, all of which have the same length of $T = 2$s. Each segment has 5 bitrate levels, i.e., 200kbps, 400kbps, 600kbps, 800kbps, 1000kbps in ascending order. The parameters mentioned in ***Bw-QoE*** are as follows. $p_1 = 0.6$, $p_2 = 0.4$, $a = 0.55$, $b = 0.45$, $B = 20$s, $B_{\min} = 4$s, $B_{\max} = 16$s. In the initial state, the video starts playing when the buffer occupancy reaches 8s.

B. PERFORMANCE ANALYSIS

In our simulations in scenarios A and B, we compare ***Bw-QoE***'s performance with that of classic LIU's strategy [11] from perceptual factors and technical factors to evaluate QoE during a video streaming session. The perceptual factors are directly perceived by end viewers, and includes the average segment bitrate, the segment bitrate distribution, the interruption times, and the switching numbers. Besides, the average buffer occupancy is a technical factor. Simulation results are shown in Fig. 3.



(a) Bandwidth in scenario A (b) Bandwidth in scenario B

(c) Segment bitrate in scenario A (d) Segment bitrate in scenario B

(e) Buffer occupancy in scenario A (f) Buffer occupancy in scenario B

FIGURE 3. Simulation results of segment request strategy.

1) AVERAGE SEGMENT BITRATE

Average segment bitrate reflects an overall situation of the video bitrate, and it can be expressed as:

$$AverageSegmentBitrate = \frac{1}{N}\sum_{n=1}^{N} r_n \tag{25}$$

where r_n represents the bitrate of the n-th segment. As shown by Fig. 3(c) and 3(d), the bitrate of a segment requested by ***Bw-QoE*** is equals to or higher than LIU's strategy in most cases. Besides, according to Eq. (25), both of their average bitrates in scenario A and B are shown in Table 1. Obviously, the segment average bitrate of ***Bw-QoE*** is about 8%-10% higher than LIU's strategy. Higher average bitrate brings higher video definition and better viewing effect, so naturally ***Bw-QoE*** can optimize user's QoE.

2) SEGMENT BITRATE DISTRIBUTION

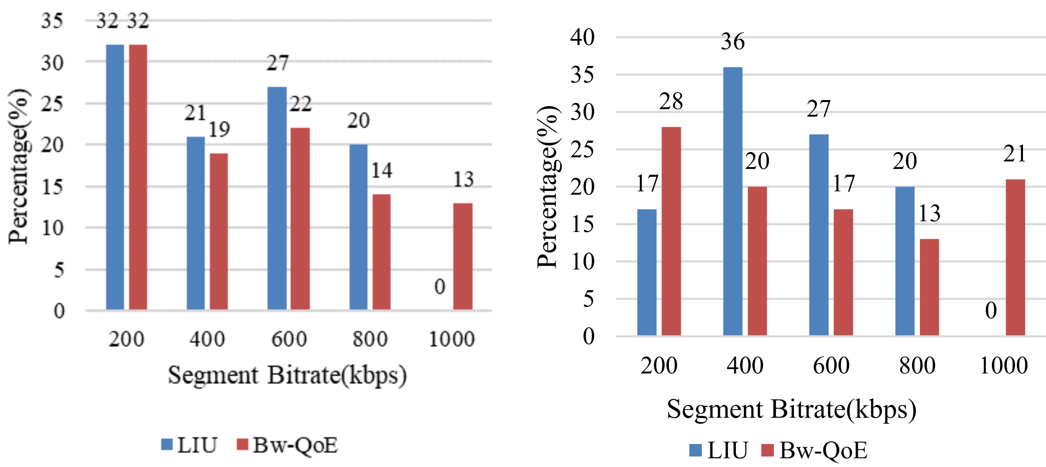
Segment bitrate distribution reflects the specific proportion of each bitrate. Fig. 4 shows the statistical results of bitrate distribution based on Fig. 3(c) and 3(d). In ***Bw-QoE***, segments with the bitrate of 1000kbps accounts for 13%-21% while LIU's strategy has no choice for segment with 1000kbps. What's more, the segments with high bitrate (800kbps-1000kbps) in ***Bw-QoE*** is higher about 35%-41% than LIU's strategy. The results also confirm that ***Bw-QoE*** has higher average bitrate from another perspective.

TABLE 1. Segment average bitrates.

Strategy	Scenario A	Scenario B
LIU	483kbps	513kbps
Bw-QoE	523kbps	567kbps

3) INTERRUPTION TIMES

As usual, interruption seriously affects user's viewing during the video playback and leads to a decrease in QoE. As constrained by the buffer underflow, Bw-QoE maintains a smooth playback shown by Fig. 3(e) and 3(f). However, Fig. 3(e) shows that LIU's strategy has two interruptions (i.e. the buffer occupancy is 0) which occur at the 5-th segment to the 8-th segment, and the 16-th segment to the 20-th segment. The interruptions last about 6s-8s. The results show that Bw-QoE can effectively avoid interruption during the video playback.



(a) Segment bitrate distribution in scenario A

(b) Segment bitrate distribution in scenario B

FIGURE 4. Segment bitrate distributions.

4) BITRATE SWITCHING NUMBERS

During the viewing, segment bitrate switching which leads to the change of resolution has great effects on user's QoE. Bitrate switching numbers can be computed by the following equation.

$$BitrateSwitchingNumbers = \sum_{n=2}^{N} sn(n)$$
$$sn(n) = \begin{cases} 1, & r_n \neq r_{n-1} \\ 0, & r_n = r_{n-1} \end{cases} \tag{26}$$

where sn(n) denotes the event index of the bitrate switching between two consecutive segments. In a video streaming session, if the bitrate of the n-th segment is different from that of the previous (n-1)-th one, then sn(n) equals to 1. As shown in Table 2, Bw-QoE decreases switching numbers about 15%-17%, and provides a better viewing experience in the same scenario. What's more, in the same strategy, the bitrate switching of segment in scenario B is more frequently than that in scenario A, which is also consistent with the severe bandwidth fluctuations in scenario B.

TABLE 2. Bitrate Switching numbers.

Strategy	Scenario A	Scenario B
LIU	40	67
Bw-QoE	34	55

5) AVERAGE BUFFER OCCUPANCY

The average buffer occupancy shows how many segments are buffering in buffer. A larger buffer occupancy in client player can ensure robustness to further playback interruptions. When the network bandwidth deteriorates suddenly, the buffering segments will counteract adverse impacts caused by bandwidth fluctuations, and prevent buffer underflow to an extent. The average buffer occupancy can be expressed as:

$$AverageBufferOccupancy = \frac{1}{N}\sum_{n=1}^{N} q(n) \tag{27}$$

where $q(n)$ denotes the buffer occupancy after the n-th segment arrives at buffer completely. Table 3 is the statistics of Fig. 3(e) and 3(f). In scenario A and B, the average buffer occupancy in ***Bw-QoE*** is about 13%-51% larger than that of LIU's strategy, which means that buffer underflow is less likely to happen in ***Bw-QoE***.

TABLE 3. Average buffer occupancy.

Strategy	Scenario A	Scenario B
LIU	4.04s	5.86s
Bw-QoE	6.14s	6.64s

C. FURTHER ANALYSIS IN BANDWIDTH ESTIMATION

The above comparison shows that Bw-QoE has better performance than LIU's strategy, and effectively improves QoE. On the basis of the simulation results, we furthermore analyze the causes of different performance between two strategies from the aspect of bandwidth estimation. In LIU's strategy, the bandwidth fluctuation is detected by the bandwidth estimation factor μ, which is defined as the ratio of MSD (Media Segment Duration) to SFT (Segment Fetch Time), and is used to determine whether the bitrate of the current segment matches the end-to-end bandwidth of path. Once probing the spare network capacity, a step-wise switching-up method is used to switch to a higher bitrate. Upon detecting a network congestion, an aggressive switching-down method is deployed to prevent playback interruptions. However, Bw-QoE considers the constraints of buffer, and acquires the trend of real available bandwidth by bandwidth estimation. As detailed in Eq. (3) and Eq. (4), different methods are

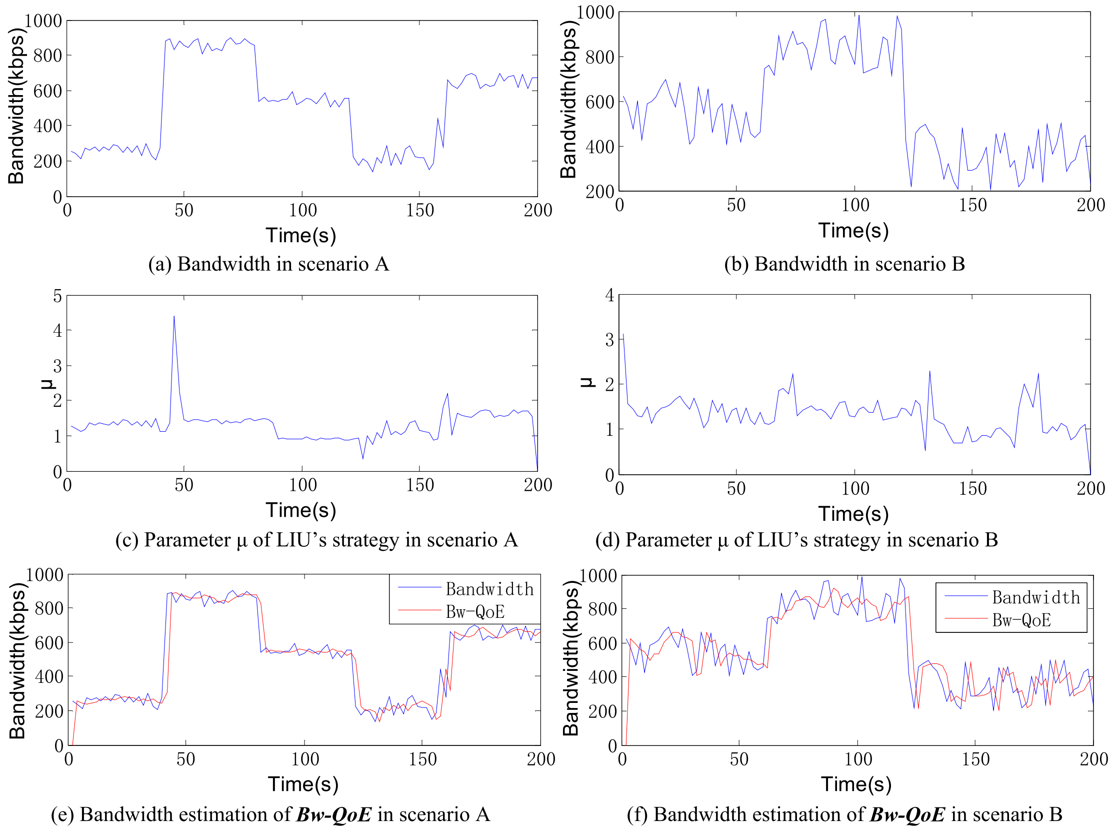


FIGURE 5. **Simulation results of bandwidth estimation.**

applied to estimate the available bandwidth during a video streaming session. In LIU's strategy, μ determines only the trend of bandwidth change, and Bw-QoE estimates the available bandwidth of the next moment. We make a comparison about their feasibilities in perceiving bandwidth change, as shown by Fig. 5.

Fig. 5(a) and 5(b) illustrate the bandwidth fluctuation in two network simulation scenarios, respectively. In Fig. 5(c), if the available bandwidth is stable, μ maintains at 1, which means the rate of playback and download are approximately equal. When the available bandwidth suddenly rises or falls, μ will increase or decrease accordingly, which results in the bitrate switching of the next segment. After adjusting the bitrate, the playback rate matches download rate, and μ returns to 1 again. However, in scenario B where the bandwidth fluctuation is severe, μ could not reflect the change trend of bandwidth visually, which eventually affects subsequent bitrate selection. As shown by Fig. 5(e) and 5(f), ***Bw-QoE*** estimates the available bandwidth effectively, which can provide an accurate bandwidth in bitrate selection, and optimize user's QoE eventually.

IV. CONCLUSION

In connected vehicle network-enabling ITS environment, the video streaming driver-assistant services in an acceptable quality is very useful to road safety, traffic efficiency, and infotainment. However, the high-speed mobility of the vehicle is a severe obstacle to the reliable video streaming of ITS and the Quality of Experience (QoE) of vehicular users. It is crux for ITS service providers how to improve users' QoE through an adaptive video segments request strategy. In HTTP adaptive streaming, an adaptive strategy to request video segments with the most appropriate bitrate can provide users with the best viewing experience. Aiming at an adaptive matching among segment bitrate, network bandwidth and buffer occupancy, we proposed a bandwidth-aware video segment request strategy to optimize user's QoE, i.e., Bw-QoE. Based on the estimated bandwidth and the requirements of avoiding buffer underflow, overflow and unuseful download, Bw-QoE can request a segment with the most appropriate bitrate to maximize the user's QoE. Simulation results showed that in both stable network and variable network with severe bandwidth fluctuations, Bw-QoE increases video bitrate (about 8%-10%), reduces playback interruption (about 100%), reduces bitrate switching (about 15%-17%), and increases buffer occupancy (about 13%-51%), which confirms that Bw-QoE efficiently optimizes QoE for users.

REFERENCES

[1] D. Manimozhi, S. Karthik, V. Sivasankaran, A. A. Mohammed, and A. Nithya, "An effective high quality video streaming protocol with optimal path selection for VANET," in *Proc. Int. Conf. Commun. Signal Process. (ICCSP)*, Chennai, India, Apr. 2018, pp. 0272–0275.

[2] Z. Ning, K. Zhang, X. Wang, M. S. Obaidat, L. Guo, X. Hu, B. Hu, Y. Guo, B. Sadoun, and R. Y. K. Kwok, "Joint computing and caching in 5G-envisioned Internet of vehicles: A deep reinforcement learning-based traffic control system," *IEEE Trans. Intell. Transp. Syst.*, early access, Feb. 5, 2020, doi: 10.1109/TITS.2020.2970276.
[3] "Cisco visual networking index: Global mobile data traffic forecast update, 2016–2021," White Paper, Feb. 2017.
[4] Z. Ning, K. Zhang, X. Wang, L. Guo, X. Hu, J. Huang, B. Hu, and R. Y. K. Kwok, "Intelligent edge computing in Internet of vehicles: A joint computation offloading and caching solution," *IEEE Trans. Intell. Transp. Syst.*, Jun. 5, 2020, doi: 10.1109/TITS.2020.2997832.
[5] Y. Sani, A. Mauthe, and C. Edwards, "Adaptive bitrate selection: A survey," *IEEE Commun. Surveys Tuts.*, vol. 19, no. 4, pp. 2985–3014, 4th Quart., 2017.
[6] Z. Ning, P. Dong, X. Wang, X. Hu, L. Guo, B. Hu, Y. Guo, T. Qiu, and R. Y. Kwok, "Mobile edge computing enabled 5G health monitoring for Internet of medical things: A decentralized game theoretic approach," *IEEE J. Sel. Areas Commun.*, Mar. 2020.
[7] M. T. A. Abdullah, J. Lloret, A. C. Solbes, and L. García-García, "Survey of transportation of adaptive multimedia streaming service in Internet," *Netw. Protocols Algorithms*, vol. 9, nos. 1–2, pp. 125–185, Jun. 2017.
[8] J. Park, J.-N. Hwang, Q. Li, Y. Xu, and W. Huang, "Optimal DASH-multicasting over LTE," *IEEE Trans. Veh. Technol.*, vol. 67, no. 5, pp. 4487–4500, May 2018.
[9] M. Seufert, S. Egger, M. Slanina, T. Zinner, T. Hoßfeld, and P. Tran-Gia, "A survey on quality of experience of HTTP adaptive streaming," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 1, pp. 469–492, 1st Quart., 2017.
[10] T. Thang, Q.-D. Ho, J. Kang, and A. Pham, "Adaptive streaming of audiovisual content using MPEG DASH," *IEEE Trans. Consum. Electron.*, vol. 58, no. 1, pp. 78–85, Feb. 2012.
[11] C. Liu, I. Bouazizi, and M. Gabbouj, "Rate adaptation for adaptive HTTP streaming," in *Proc. ACM Conf. Multimedia Syst.*, San Jose, CA, USA, 2011, pp. 169–174.
[12] C. Müller, S. Lederer, and C. Timmerer, "An evaluation of dynamic adaptive streaming over HTTP in vehicular environments," in *Proc. 4th Workshop Mobile Video (MoVid)*, Chapel Hill, NC, USA, 2012, pp. 37–42.
[13] D. Raca, A. H. Zahran, C. J. Sreenan, R. K. Sinha, E. Halepovic, R. Jana, V. Gopalakrishnan, B. Bathula, and M. Varvello, "Incorporating prediction into adaptive streaming algorithms: A QoE perspective," in *Proc. 28th ACM SIGMM Workshop Netw. Oper. Syst. Support Digit. Audio Video (NOSSDAV)*, Amsterdam, The Netherlands, 2018, pp. 49–54.
[14] K. Diab and M. Hefeeda, "MASH: A rate adaptation algorithm for multiview video streaming over HTTP," in *Proc. IEEE INFOCOM Conf. Comput. Commun.*, Atlanta, GA, USA, May 2017, pp. 1–9.
[15] V. P. M. Kumar and S. Mahapatra, "Quality of experience driven rate adaptation for adaptive HTTP streaming," *IEEE Trans. Broadcast.*, vol. 64, no. 2, pp. 602–620, Jun. 2018.
[16] *Methods for Subjective Determination of Transmission Quality*, document ITU Rec P. 800, 2003.
[17] C. Timmerer, A. Zabrovskiy, and A. Begen, "Automated objective and subjective evaluation of HTTP adaptive streaming systems," in *Proc. IEEE Conf. Multimedia Inf. Process. Retr. (MIPR)*, Miami, FL, USA, Apr. 2018, pp. 362–367.
[18] T. Karagkioules, C. Concolato, D. Tsilimantos, and S. Valentin, "A comparative case study of HTTP adaptive streaming algorithms in mobile networks," in *Proc. 27th Workshop Netw. Oper. Syst. Support Digit. Audio Video (NOSSDAV)*, Taipei, Taiwan, 2017, pp. 1–6.
[19] W. Liu, "Design and implementation of dynamic adaptive streaming media system based on HTTP," M.S. thesis, Shenzhen Graduate School, Harbin Inst. Technol., Harbin, China, 2014.
[20] N. H. Anderson, "Primacy effects in personality impression formation using a generalized order effect paradigm.," *J. Personality Social Psychol.*, vol. 2, no. 1, pp. 1–9, 1965.
[21] E. D. Gelasca and T. Ebrahimi, "On evaluating video object segmentation quality: A perceptually driven objective metric," *IEEE J. Sel. Topics Signal Process.*, vol. 3, no. 2, pp. 319–335, Apr. 2009.

JUZHENG DUAN received the M.S. degree from Lanzhou Jiaotong University, Gansu, China, in 2012. He is currently pursuing the Ph.D. degree in communication and information systems with the University of Science and Technology Beijing, Beijing. His research interests include the next-generation Internet, content delivery network, and connected vehicle networks.

KUN LI received the M.S. degree from the University of Science and Technology Beijing, in 2019. She is currently working with the Beijing Institute of Aerospace Control Devices. Her research interests include video content distribution network and satellite communication.

YUN HE received the M.S. degree from the China University of Mining and Technology at Beijing, Beijing, China, in 2016. She is currently pursuing the Ph.D. degree in communication and information systems with the University of Science and Technology Beijing, Beijing. Her research interests include network security and privacy protection.

MIN ZHANG is currently an Associate Professor with the School of Computer and Communication Engineering (SCCE), University of Science and Technology Beijing, Beijing, China. Her researches focus on content distribution networking and network security. She has fulfilled more than ten research projects, including the National Natural Science Foundation of China and the National Hi-Tech Research and Development Program (863 Program). In her research field, she authored more than 60 articles and holds 30 patents.

XIAOLONG YANG (Member, IEEE) received the B.Eng., M.S., and Ph.D. degrees in communication and information systems from the University of Electronic Science and Technology of China, Chengdu, China, in 1993, 1996, and 2004, respectively. He is currently a Professor with the School of Computer and Communication Engineering, Institute of Advanced Networking Technologies and Services, University of Science and Technology Beijing, Beijing, China. He has fulfilled more than 30 research projects, including the National Natural Science Foundation of China, the National Hi-Tech Research and Development Program (863 Program), and the National Key Basic Research Program (973 Program). His current research interests include optical switching and Internetworking and the next-generation Internet. He has authored more than 80 articles and holds16 patents in these areas.