QoE-Aware Resource Allocation for Adaptive Device-to-Device Video Streaming

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Abstract

The continuing advances in the storage and transmission abilities of user equipment have made it possible to share videos through device-to-device (D2D) communications, which may be an efficient way to enhance the capacity of cellular network to provide wireless video services. In adaptive D2D video streaming, user experience is greatly influenced by the quality and fluency of the video, which is affected by the D2D link's quality. Additionally, the quality of D2D links relies on the resource allocation scheme for D2D pairs. To improve the quality-of-experience (QoE) in D2D video streaming, we propose a QoE-aware resource allocation scheme for adaptive D2D video streaming. The QoE-aware resource allocation scheme has the ability to cater to the user experience in adaptive video steaming while considering the co-channel interference derived from frequency reuse in D2D communications. Specifically, a dynamic network scheduling problem is formulated and solved, whose objective is to maximize the video quality while maintaining the long-term stable performance of fluency during video playback. Extensive numerical results demonstrate the performance comparison between the proposed QoE-aware resource allocation scheme and the QoE-oblivious resource allocation scheme.

Index Terms

Quality-of-experience, device-to-device, video on demand, adaptive video streaming, resource allocation.

I. Introduction

Demand for video content over wireless network is growing at a tremendous rate. The ratio of mobile video traffic to the overall mobile traffic will exceed 69 percent by 2019 in the prediction of Cisco Visual Networking Index [1]. Meanwhile, a large proportion of video traffic is taken up by on-demand video streams, which have a characteristic that a few popular on-demand videos are viewed by a majority of users at different time. This characteristic could be utilized to improve the capacity of mobile networks for providing on-demand videos. Specifically, caching popular files in user devices offers opportunities to share mobile videos through device-to-device (D2D) communications [2]. D2D communication in cellular networks is defined as the direct communication between two mobile users without data routing through the base station (BS) [3]. Moreover, the introduction of D2D technology contributes to capacity enhancement of cellular networks by reusing the cellular spectrum.

The motivation for wireless D2D caching networks is that users can gain videos from adjacent mobile devices through D2D communications without requesting data from BSs. Note that the process of video streaming usually has quality-of-experience (QoE) requirements for users. When multiple video streams are delivered through D2D communications, how to complete the video streaming process while maintaining the user experience becomes a challenging issue. Indeed, the interference caused by resource reuse in D2D communications has negative effects on the communication quality of links involved, while the quality and fluency of streaming videos are greatly influenced by the fluctuant wireless channel quality. Additionally, the quality and fluency of streaming videos greatly affect the user experience. Hence, it is significant to effectively allocate radio resource to D2D links while considering the user experience in D2D video streaming.

To this end, we propose a QoE-aware resource allocation scheme for the case that multiple D2D pairs request video streaming in a cell. Specifically, the target of radio resource allocation is to maximize the time-averaged quality of video streams transmitted over D2D communications, while constraining the number of stall events for each stream. The performance of D2D video streaming can be improved with the QoE-aware resource allocation scheme in comparison with the QoE-oblivious resource allocation scheme. In summary, we propose a QoE-aware resource allocation scheme for D2D video streaming, which is crucial for improving the user experience. Specifically, the resource allocation problem is formulated as a dynamic network scheduling problem. Moreover, we obtain the optimal solution to the resource allocation problem according to the theory of Lyapunov drift and Lyapunov optimization. Extensive numerical results confirm the QoE performance improvement of D2D video streaming with the proposed scheme.

In the following section we introduce the background of on-demand video streaming and D2D communication. The D2D video streaming system is then presented. We formulate and solve the QoE-aware radio resource allocation problem for the adaptive D2D video streaming, followed by numerical results showing the performance of the QoE-aware radio resource allocation scheme and the QoE-oblivious radio resource allocation scheme. Conclusions and future directions are given in the final section.

II. D2D Video Sharing and QoE in Adaptive Video Streaming

In this section, we introduce some preliminaries on D2D video sharing and QoE in adaptive video streaming, which serve as the basis of the proposed QoE-aware video streaming scheme in this article.

A. D2D Video Sharing

Considering the fact that popular on-demand videos are viewed by multiple users at different time, it is beneficial to cache popular video files into mobile devices in advance. When a video is requested by a user (user A as indicated in Fig. 1) whose neighbor (helper A in Fig. 1) has cached that video, video streaming can be realized over the D2D communication between user A and helper A, rather than over the traditional cellular link between user A and the BS, as shown in Fig. 1. The overview of D2D video sharing system is as follows.

1) Video caching: D2D caching is a process to store popular video files in the local memory of mobile users, which are called helpers and distributed in the cellular network. Then other mobile users can acquire videos from the helpers through D2D communication, rather than by querying data from the BS. The opportunity of video delivery through D2D communication can be improved with an effective caching scheme, which may consider factors such as geographic location, probability of video being requested, and social relationship [2].

2) Pair matching: When a video is requested by a mobile user in the cellular network, an appropriate provider needs to be selected to offer that video. The provider may be the BS or an adjacent helper who has cached that video. Pairing user with helper can be done with the help of the BS, which may consider factors such as geographic location, social relationship to improve system performance and/or communication link quality [4].

3) Resource allocation: Specified radio resources are required to establish D2D communication links for pairs which have been matched via the previous step. When multiple D2D pairs are in need of the limited radio resources, an efficient resource allocation scheme becomes essential to improve the system performance and ensure the user experience. For example, maximizing the system throughput is the target in [3], and QoS requirements for both D2D and cellular users are guaranteed in [5]. Unfortunately, the existing schemes cannot fully utilize the available radio resource to improve the user experience when adaptive video streams are transmitted over D2D links, without considering the process of rebuffering and the adaptive quality levels of video streams [6]. Our study focuses on QoE-aware resource allocation for adaptive D2D video streaming.

4) Video streaming over D2D links: After the above steps, D2D links can be established between D2D pairs that have been allocated radio resources. Video data is then requested by the user and transmitted from the helper over the established D2D links. The user downloads video data into the buffer. Meanwhile the video data, which has been stored in the buffer before, is fetched by the video player and viewed by the user. When the buffered data is not enough, stall events occur until sufficient video data is downloaded into the buffer.

B. QoE in Adaptive on-demand Video Streaming

In adaptive on-demand video streaming (e.g., Dynamic Adaptive Streaming over HTTP), the video is divided into sequential chunks, which are encoded and decoded as independent units. Further, each chunk may hold multiple versions that are encoded at different bit rates and quality levels [7]. Note that chunks can be requested and decoded separately, the client's playback buffer size can be controlled by dynamically adjusting the quality level at which new chunks are transmitted. For example, if the buffer is nearly empty, low bit rate can be selected for new chunks in order to quickly fill up the buffer in avoidance of stall events.

We focus on two vital aspects that greatly influence the user experience in adaptive video streaming [8].

- **Stall events:** The video data is stored in the buffer when the user receives it, meanwhile the video data is fetched from the buffer when the video player retrieves it. If the rate of retrieving the data is greater than the rate of receiving (due to links with poor quality), the buffer will be empty. When the chunks in the buffer is not enough to sustain the playback, the video player has to pause until sufficient data is stored in the buffer. In this case, stall events annoy the viewer and have negative effect on the user experience.
- **Visual experience:** The same video content may have different perceptual quality when it is encoded at different quality levels and bit rates. In adaptive video streaming, the quality levels of the transmitted video chunks affect the user experience, owing to the fact that the viewer prefers a higher quality of videos that are encoded at a higher quality level.

In adaptive on-demand video streaming, users expect to watch videos with as high as possible quality levels and limited stall events. However, a higher quality level is encoded at a higher bit rate, which may exceed the capacity of the communication link and lead to stall events. Then it is crucial to select an appropriate quality level for each video chunk in order to improve the user experience. This process can be called rate adaptation. Rate adaptation algorithms in cellular networks have been studied by many researchers. In [7], the rate adaptation algorithm tries to match the video rate to the link throughput, which is calculated by leveraging the throughput value averaged over the last downloaded packets. The link throughput can also be estimated if the wireless channel prediction information is known by the video streaming application [9].

In summary, most designs for D2D resource allocation are aimed at improving the system performance, such as the system throughput, the network capacity and so on. The system performance may be optimal when the spectrum is reused by a group of D2D pairs. However, some D2D links may have poor channel states due to the interference caused by other links in the group. When adaptive video streams are transmitted over the above mentioned D2D links, video quality level has to be passively adapted to the poor channel, thus leading to a poor video quality and awful user experience. In addition, we note that a higher video quality level means more stall events when the rate of the link is poor. Furthermore, users may have different preferences between video quality and the tolerance of stall events due to personal character. Therefore the flexible tradeoff between video quality level and stall events is crucial to cater to differential user experience in adaptive video streaming.

III. QoE-aware Adaptive D2D Video Streaming

To make better use of the available radio resource to cater to the user experience, we propose a QoE-aware adaptive D2D video streaming system as illustrated in Fig. 2, we focus on the resource allocation and the rate adaptation for multiple D2D pairs.

1) Indices preparation: Time is partitioned into discrete slots, also called execute cycles. At the beginning of each slot, indices indicating the user experience are transferred from users to the scheduler, and channel states are acquired by the BS. The scheduler, for example, can be placed at the BS.

2) Decision making: According to the QoE indices and the channel states, the scheduler makes joint decisions of resource allocation and video quality level selection. The aim is to allocate the available radio resource and adapt the video quality levels over time in order to deliver the best possible quality video to the user, subject to the network conditions. Additionally, the flexible tradeoff between video quality levels and stall events can be achieved in the scheme.

3) Execution: After the decisions are made by the scheduler, the video at the selected quality level is transmitted over the D2D link which has been allocated radio resources. When the user receives video data, the process of buffering and playing generates QoE indices.

The QoE indices of all users are transferred to the scheduler in each slot, and decisions of the resource allocation and the video quality level selection are updated in each slot, in order to accommodate to the varying wireless channel state. Next, we describe the system model for the adaptive D2D video streaming system. The notations used in this article are summarized in Table I.

A. Communication Model

As illustrated in the upper part of Fig. 3, we assume that there is one channel available for N D2D pairs to access, and D2D pairs keep stationary during every slot while their positions may vary from slot to slot [10]. Each D2D pair is indexed by $u = 1, 2, \cdots, N$, and each slot is indexed by $t = 0, 1, 2, \cdots, \infty$.

The channel can be reused by a group of D2D pairs. $\mathbf{P}(t)$ is a vector whose u-th element is a binary variable $P_u(t)$ indicating whether D2D pair u is able to access the channel at slot t, as illustrated in the bottom part of Fig. 3. If the resource reuse pattern is determined by the scheduler and the channel gain is obtained from the channel state reports, the rate of D2D pairs can be derived as $\mathbf{R}(t)$ whose u-th element $R_u(t)$ represents the rate of D2D pair u at slot t. The channel gain of each link should be estimated by channel probing and passed to the BS at the beginning of each slot. For $2N$ devices with N transmitters and N receivers, there would be N^2 channel quality information (CQI) overhead at the BS for all possible D2D links.

B. Video Streaming Model

There are multiple quality levels for video streams which are transmitted over D2D communications. $\mathbf{l}(t)$ is a vector whose u-th element is $l_u(t)$ representing the video quality level of chunks which are transmitted to user u at slot t. We define $I_u(t)$ as an index to indicate the video quality loss of chunks, which are transmitted to user u at slot t. For simplicity, if a chunk's quality level is selected as l while the highest level is L, this chunk has a quality loss of $L - l$. Total quality loss of all chunks transmitted to user u at slot t is denoted as $I_u(t)$.

In an execute cycle, video chunks at the selected level $\mathbf{l}(t)$ are transmitted over the involved D2D links $\mathbf{P}(t)$ after the scheduler making decisions. The playing time of chunks which are transmitted to user u at slot t is defined as $b_u(t)$. $b_u(t)$ equals $\Phi_u(R_u(t) \cdot T_{slot})$, where $\Phi_u(*)$ is a function to compute the playing time of chunks transmitted to user u [11]. Simply stated,

$b_u(t)$ is decided by the data size and encoded bit rate of the transmitted chunks. The data size is determined by the rate of D2D link $R_u(t)$, while the encoded bit rate depends on the quality level $l_u(t)$ and the characteristics of variable bit rate (VBR) videos [11].

At the beginning of each slot, the video player checks up whether the buffered data is enough to support the playback for that slot. Once it is not enough, the playback stalls while the user continues to receive video data. The buffered data is checked up again until the stall time amounts to a fixed length. If the buffered data is enough to support the playback for current slot, the playback continues. Otherwise, the number of stall events increases by one and a new stall event occurs.

IV. QoE-Aware Radio Resource Allocation

In this section, we focus on the process of QoE-aware resource allocation for D2D pairs which have been matched for adaptive video streaming.

A. Problem formulation

To manage the resource in a long-term way, we formulate the QoE-aware resource allocation problem as a dynamic scheduling problem [12]. The objective is to minimize the "time-averaged" total quality loss for all video streams, and the constraint represents controlling the "long-term" fluency for every stream.

$$\begin{aligned} &\min \lim_{t\to\infty} \tfrac{1}{t} \sum_{\tau=0}^{t-1} \sum_{u=1}^{N} E[I_u(\tau)] \\ &\text{s.t.} \quad Q_u(\tau) \text{ is stable for every user,} \end{aligned} \tag{1}$$

where $Q_u(t)$ is defined as a virtual queue for user u at the beginning of slot t in order to depict the long-term fluency of the video stream. Its initial value (i.e., $Q_u(0)$) is a positive constant ensuring that $Q_u(t)$ is positive, while the updating equation of the queue is that $Q_u(t+1)$ equals $Q_u(t) - b_u(t) + a_u(t)$. Specifically, $b_u(t)$ is the playing time of the data which is transmitted to user u at slot t. $a_u(t)$ is the playing time at slot t if user u watches video without any stall events. In other words, $a_u(t)$ equals the length of a slot, i.e., T_{slot}. Keeping the queue stable is beneficial to controlling stall events in video streaming. For example, if $a_u(t)$ equals $b_u(t)$ for every slot, the queue will keep stable and the received data in every slot will sustain the fluent playback for any slot. It means that the video can play without any stall events if an arbitrary initial buffer exists. In addition, $Q_u(t)$ can be updated according to the actual transmission for user u at the previous slot, and it could be transmitted to the BS as a QoE index at the beginning of each slot.

The dynamic problem is aimed at improving the user experience by minimizing the time-averaged quality loss while maintaining the long-term stable performance of fluency in adaptive D2D video streaming. However, it is difficult to find a direct solution since the network state is varying over time. Therefore, we need to break problem (1) into sub-problems for every slot.

B. Obtaining an Optimal Solution

Based on the Lyapunov drift-plus-penalty method in [12], [13], the optimization problem for every slot can be formulated according to problem (1).

$$\begin{aligned} &\max \ \sum_u Q_u(t) \cdot b_u(t) - V \sum_u I_u(t) \\ &\text{s.t.} \quad \alpha(\mathrm{t}) \in \mathrm{A}_{\omega(\mathrm{t})}, \end{aligned} \tag{2}$$

where $V > 0$ is a control parameter of the drift plus penalty policy which affects a utility-delay tradeoff. The constraint means that the control action $\alpha(t)$, which contains the resource reuse pattern $\mathbf{P}(t)$ and the quality level $\mathbf{l}(t)$, is feasible for the network state $\omega(t)$.

To get the solution of problem (2), the analysis is described as follows. In the case that the resource reuse pattern is determined as $\mathbf{P}(t)$, we can obtain the signal-to-interference-plus-noise ratio of user u at slot t, which is called as $SINR_u(t)$. At the receiver of D2D pair u, the interference is the sum strength of the received signals from the transmitters of other active D2D pairs in $\mathbf{P}(t)$. Then, $R_u(t)$ can be calculated by

$$R_u(t) = B \cdot \log_2(1 + SINR_u(t)). \tag{3}$$

In the next step, we need to select an optimal quality level $\mathbf{l}(t)$ for the determined $\mathbf{P}(t)$. Given a determined $R_u(t)$, the selection of the optimal $\mathbf{l}(t)$ can be considered separately for each user. It means that we need to select an optimal $l_u(t)$ which maximizes $Q_u(t) \cdot b_u(t) - V \cdot I_u(t)$ for each user.

In other words, there is a tradeoff between the video quality and the queue backlog when selecting the optimal $l_u(t)$ for the determined $R_u(t)$. For example, if $R_u(t)$ is determined, we will select a high quality level $l_u(t)$ when the queue is nearly empty, and select a low quality level $l_u(t)$ when the queue is too long. Specifically, in the case that two quality levels are available for $l_u(t)$, there is a threshold queue value for helping select the optimal $l_u(t)$. If the queue value

$Q_u(t)$ is bigger than that threshold, the higher one of the two levels will be selected, otherwise the lower one will be selected. The threshold can be derived by the value of V and the average bit rates of video stream u at slot t with the two quality levels. Even though the average bit rate may vary with time due to VBR characteristics, the value of V can affect the threshold and then decides the weight ratio of quality loss to queue backlog in the point of statistics. Increasing the value of V means a more importance of video quality, and decreasing the value of V means a more importance of removing queue backlog.

Based on the analysis above, we know that each feasible resource reuse pattern $\mathbf{P}(t)$ corresponds to an optimal quality level $\mathbf{l}(t)$. The solution of problem (2) is to select the optimal resource reuse pattern (with the corresponding quality level), which can maximize the objective of problem (2) among all feasible resource reuse patterns.

V. Numerical Results

In this section, extensive numerical results show the performance comparison between the proposed QoE-aware resource allocation scheme and the QoE-oblivious resource allocation scheme. In the QoE-oblivious scheme, the process of resource allocation follows the max-sum rate rule in [6], and the rate adaptation algorithm is adopted as [14]. Note that the distance between two devices significantly affects the performance of D2D video streaming. The existing works show that D2D communication can have a satisfactory performance when the receiver and transmitter of the D2D pair are proximal to each other [4]. We set the distance between the transmitters and receivers of D2D pairs accordingly. As for video streams, we adopt the Sony Demo which is encoded in MPEG4 with four different quality levels [15]. Then, we compare the performance of the QoE-aware scheme with the QoE-oblivious scheme in the following three evaluation metrics: number of stall events, video quality levels and PSNR (Peak Signal-to-Noise Ratio). All results are averaged by multiple tests.

The performance of the QoE-aware scheme changes with the variation of parameter V, which controls the tradeoff between the video quality and the number of stall events. A bigger V means a greater importance of the video quality as well as a bigger queue backlog. To observe the effect of V, other parameters are set to be fixed. When the bandwidth of the channel (represented as B) is set to be 2MHz, the results are shown in Fig. 4. The performance of the QoE-oblivious scheme is basically unchanged when B is fixed. As for QoE-aware scheme, the quality level increases with the increase of V. If V is large enough, e.g., the value of V exceeds 200, the quality level in the QoE-aware scheme becomes higher than the quality level in the QoE-oblivious scheme. However, if V is set too large, e.g., V is bigger than 550, stall events start to occur in the QoE-aware scheme. The reason is that a too large V means a video with too high quality level, which exceeds the load capacity of the channel with the limited bandwidth. An appropriate value range for V, e.g., $200 < V < 550$, can help the QoE-aware scheme provide better QoE performance than the QoE-oblivious scheme, since the former can provide higher quality levels than the latter without adding the number of stall events.

The performance of both schemes is influenced by the bandwidth of the channel, a larger bandwidth means a greater capacity to transmit videos at higher quality levels. To observe the effect of the bandwidth, other parameters are set to be fixed. When V is set to be 650, the results are shown in Fig. 5. With the increase of bandwidth, the quality level in both schemes becomes higher and higher until the arrival of the top level. Besides, we note that the quality level and PSNR of video streams in the QoE-aware scheme are higher than those in the QoE-oblivious scheme. When the bandwidth is not sufficient, there are a few stall events existing in the QoE-aware scheme, which is the price of maintaining a relatively high quality level even with a poor bandwidth. However, this phenomenon disappears quickly with the increase of the bandwidth. When the bandwidth is relatively sufficient, e.g., bigger than 3MHz here, the QoE-aware scheme can provide better user experience than the QoE-oblivious scheme, since there is a higher quality level with smooth playback in the former scheme.

In the QoE-oblivious scheme, the number of stall events is controlled, since the video quality level is determined as the maximal one suiting for the available average link rate. However, the link rate is greatly influenced by the resource reuse pattern which is determined as the one with the maximal sum rate. Therefore, when the bandwidth is large enough for transmitting adaptive videos without stall events for all D2D pairs, the QoE-oblivious scheme cannot accommodate to the varying wireless channel without reducing the quality level. For example, if an active D2D pair in the resource reuse pattern with the maximal sum rate has a relatively poor channel state, the adopted quality level has to be reduced to the one suiting for the link's rate. As for the QoE-aware scheme, this kind of behavior can be avoided. Because when the backlog of the queue is not large, the quality loss plays a more important role in influencing the utility of the optimization problem for every slot. In a word, compared with QoE-oblivious scheme, QoE-aware scheme can make better use of the available radio resource in improving the user experience.

VI. Conclusions and Future Directions

In this article we first introduced the background of D2D video streaming, and presented the intention to design the QoE-aware resource allocation scheme for D2D video streaming. Then, the QoE-aware resource allocation problem was posed and solved. Extensive numerical results showed that the proposed scheme can achieve a better performance than the QoE-oblivious resource allocation scheme when the bandwidth is relatively abundant for smooth playback in adaptive video streaming. Possible future directions include:

- Energy consumption is a latent factor affecting the user experience, since the users prefer a long standby time of mobile devices with limited battery capacity. It is significant to study energy-aware resource allocation for D2D video streaming with the consideration of fluency in video playback.
- When the number of D2D pairs becomes huge, it is important to design an algorithm with low computational complexity for solving D2D resource allocation problem that considers the user experience in video streaming.

Acknowledgment

This work was supported in part by the Major State Basic Research Development Program of China (973 Program) with Grant number 2013CB329006, Joint Specialized Research Fund for the Doctoral Program of Higher Education (SRFDP) and Research Grants Council Earmarked Research Grants (RGC ERG) with Grant 20130142140002, and the National Science Foundation of China with Grant 61428104.

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BIOGRAPHIES

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Symbol	Description
T_{slot}	Length of a slot
N	Total number of D2D pairs
L	Total number of video quality levels
u	User $u \in \{1, 2, ..., N\}$
t	Sequence number of slot
$P_u(t)$	Resource reuse pattern for user u at slot t
$\mathbf{P}(t)$	Vector $(P_1(t), P_2(t), \cdots, P_u(t), \cdots P_N(t))$
$l_u(t)$	Quality level of chunks transmitted to user u at slot t
$\mathbf{l}(t)$	Vector $(l_1(t), l_2(t), \cdots, l_u(t), \cdots, l_N(t))$
$I_u(t)$	Quality loss of chunks transmitted to user u at slot t
$Q_u(t)$	Queue for user u at slot t
$a_u(t)$	Original video playing time for user u during slot t
$b_u(t)$	Playing time of chunks transmitted to user u at slot t
$\omega(t)$	The network state at slot t
$\alpha(t)$	Control action at slot t
$A_{\omega(t)}$	The set of feasible control actions dependent on $\omega(t)$
V	A control parameter affecting a utility-delay tradeoff
B	Bandwidth of the channel
$R_u(t)$	The rate of D2D link u at slot t
$\mathbf{R}(t)$	Vector $(R_1(t), R_2(t), \cdots, R_u(t), \cdots, R_N(t))$
$\Phi_u(*)$	Function for computing the add playback time

TABLE I: Notations used in this article.

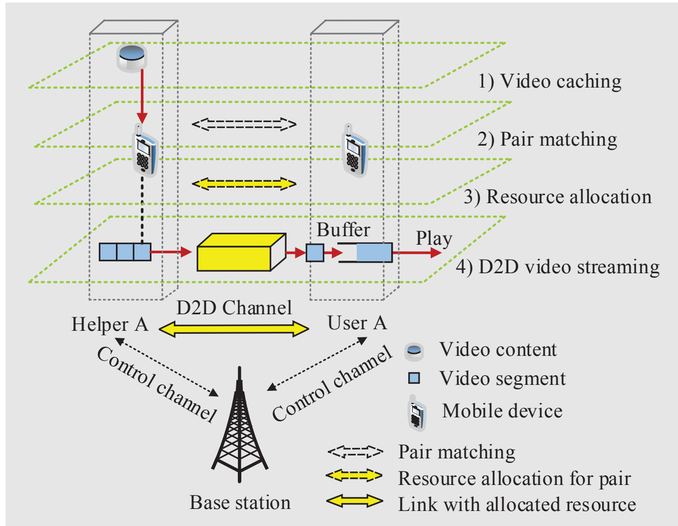

Fig. 1: D2D video sharing.

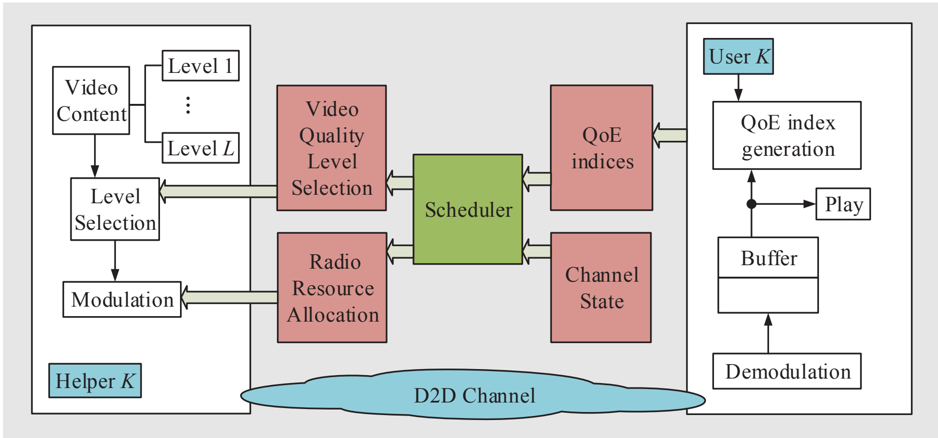

Fig. 2: An illustration of the process of QoE-aware adaptive D2D video streaming.

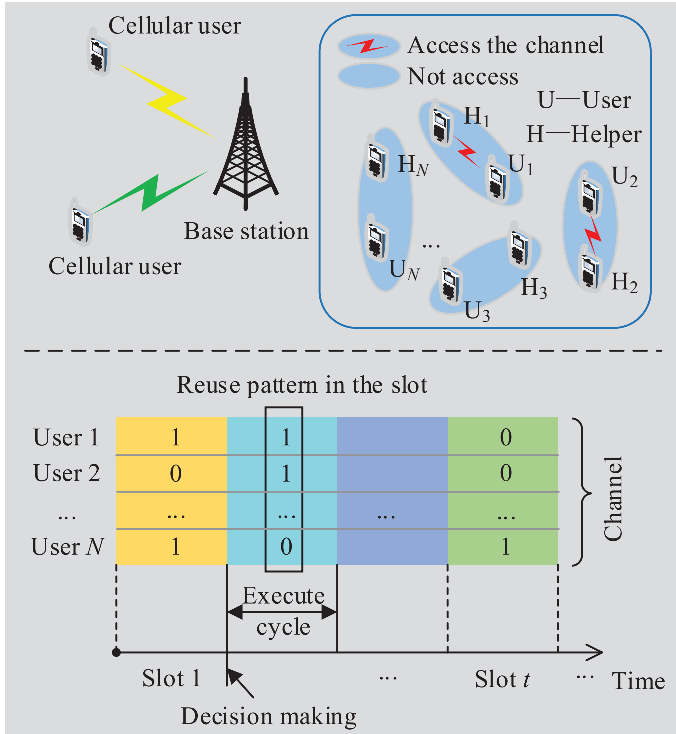

Fig. 3: Proposed QoE-aware resource allocation model for D2D adaptive video streaming.

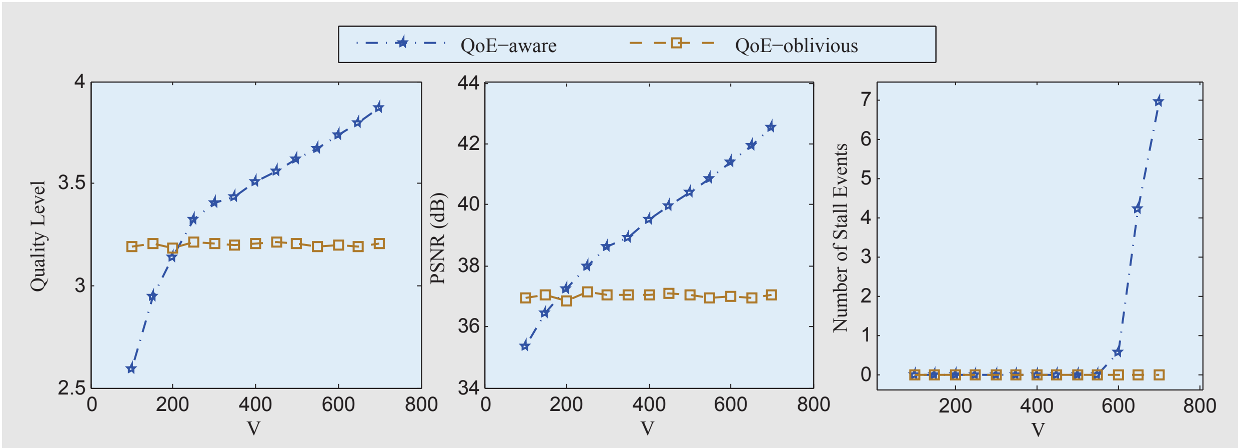

Fig. 4: Performances with different V.

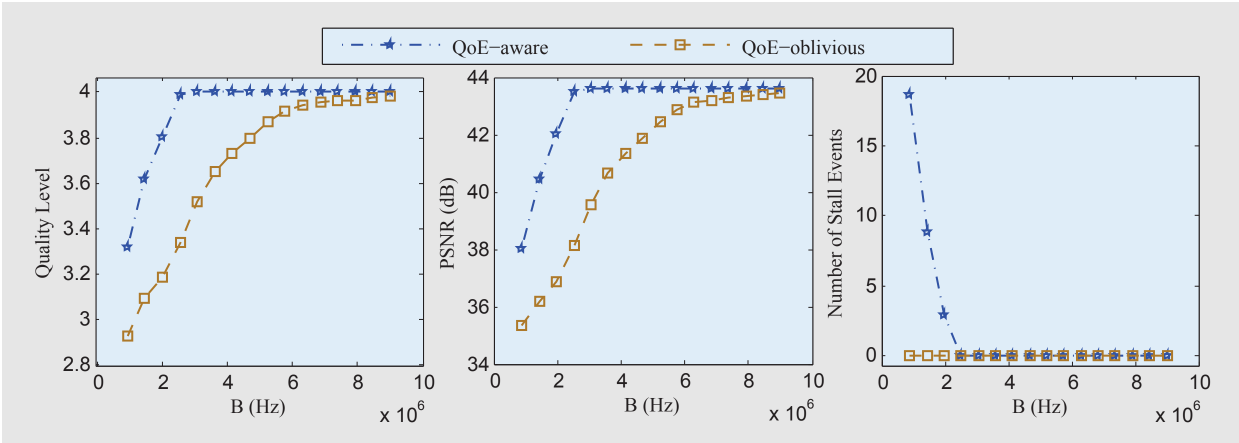

Fig. 5: Performances with different B.