Resource Sharing and Segment Allocation Optimized Video Streaming over Multi-hop Multi-path in Dense D2D 5G Networks

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Abstract. The rapid increase in mobile users (MUs) and various video applications and services (VASs) poses a set of challenges to 5G networks. Although device-to-device (D2D) communications and resource reuse techniques can improve the streaming performance of VASs, they have not utilized the fact that there are many MUs with available sharing downlink resources, namely cellular users (CUs), and many videos cached in dense MUs to establish an efficient video streaming session. In this paper, we propose a downlink resource sharing and segment allocation (RSA) optimization problem and solve it for high video streaming performance over multi-hop multi-path (MHMP) in dense D2D 5G networks. Particularly, the RSA provides a maximum capacity for the CUs that share their downlink resources with the D2D hops in each path by finding the optimal downlink resource sharing-receiving pairs between the CUs and the D2D hops. Then, the segments of a video cached in different D2D helpers (DHs) are sent to the D2D requester (DR) over the MHMP. By finding which segments are allocated to which paths for sending, the reconstructed distortion of the received segments at the DR is minimized for high playback quality. Simulation results are shown to investigate the benefits of the proposed solution compared to other schemes without RSA.

Keywords: D2D caching and communications · Downlink resource sharing · Multi-hop · Multi-path · Ultra-dense 5G networks · Video streaming

T. Q. Duong et al. (Eds.): INISCOM 2019, LNICST 293, pp. 26–39, 2019.
https://doi.org/10.1007/978-3-030-30149-1_3

1 Introduction

Device-to-device (D2D) communications and spectrum reuse techniques have been defined as the emerging solutions to improve the system capacity and resource efficiency in 5G networks [1–4]. Applying D2D communications and spectrum reuse techniques to offloading data in close proximity can further relax the macro base stations (MB) and the small-cell base stations, which have been suffered from high workload due to the rapid increase in mobile users (MUs) and various video applications and services (VASs) [5,6]. However, current studies in the literature have not utilized the fact that there are many MUs with available sharing downlink resources, i.e., cellular users (CUs), and many videos cached in dense MUs, i.e., D2D helpers (DHs), to establish an efficient multi-hop multi-path (MHMP) video streaming session of VASs.

In consideration of D2D communications and resource allocation based VASs, other additional techniques such as caching and clustering [7–10], scheduling and mode selection [11–13], and transmission [14,15], have been proposed to enhance the video streaming performance, i.e., high resource efficiency and high playback quality. The problem of these techniques is that the VASs are deployed in the context of single-hop D2D communications. On the one hand, this in turn requires high D2D transmission powers causing high interference impact on the CUs that share their downlink resources. On the other hand, the videos, which have been cached in the DHs located more than one hop far away from the requesters, are not exploited for VASs. In fact, MHMP D2D communications have been studied to gain the benefits from dense D2D 5G networks [16–20]. However, the proposed solutions are not efficient enough, especially for VASs, because they do not utilize the videos cached in the HDs for multi-source streaming nor do they consider the characteristics of the videos (e.g., rate-distortion (RD) models) and the users' behavior (i.e., represented by the video access rate/popularity) for high video streaming quality.

In addition, few of the studies have focussed on VASs over multi-source and MHMP D2D communications [21–23]. Particularly, in [21], the paths and the video traffics are scheduled to balance the energy consumption amounts of the D2D links to prolong the cooperative streaming duration of D2D networks. The authors in [22] have proposed a cross-layer solution to optimally select the D2D modes, video coding modes, and transmission paths to enhance the average quality of received video under a given energy constraint. Especially, by packetizing the video into multiple descriptions at optimal encoding rates and allocating the optimal numbers of descriptions to different DHs for being transmitted, the video is received at the D2D requester (DR) with high playback quality and low quality fluctuation while consuming low energy [23]. It can be observed that the characteristics of videos and users [21,22] and the advantages of downlink resource sharing allocation and multi-hop D2D communications [23] are not considered for high video streaming performance.

In this paper, we take the advantages of available resources of CUs and videos cached in the DHs in consideration of the characteristics of both videos and users, to propose a downlink resource sharing and segment allocation (RSA)

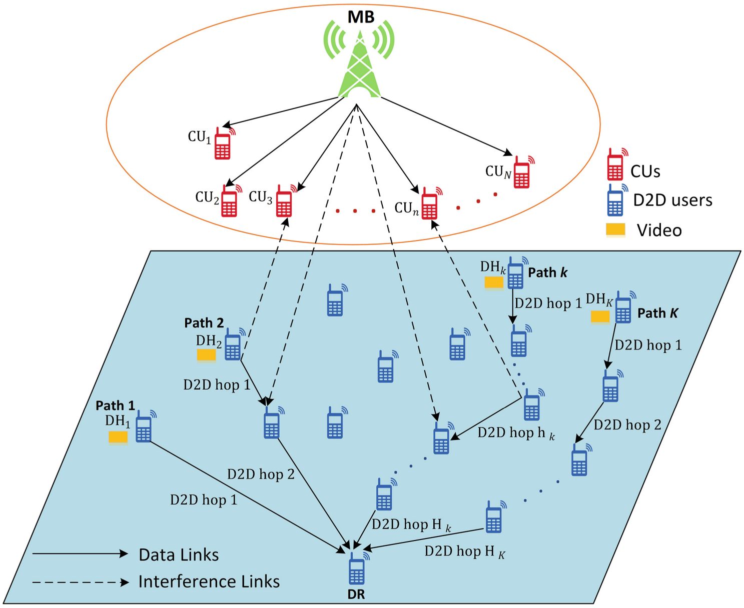

Fig. 1. VASs over MHMP in dense D2D 5G network.

optimization strategy for high performance of VASs over MHMP in dense D2D 5G networks. The RSA strategy consists of two optimization problems, namely resource sharing allocation (RA) optimization problem and segment allocation (SA) optimization problem. The RA optimization problem is solved for optimal resource sharing-receiving pairs between the CUs and the D2D hops for MHMP D2D communications. The objective is to maximize the capacity of the CUs that share their downlink resources with the D2D hops in each path. Based on the optimal results of the RA solution (all D2D hops with corresponding shared donwlink resources in each path from the DHs to the DR are identified), the SA optimization problem is then solved for optimally allocating which segments to which paths for sending. This way, the reconstructed distortion of the received video is minimized for high playback quality.

The rest of this paper is organized as follows. In Sect. 2, we introduce our system models including the VASs over MHMP in dense D2D 5G networks, downlink resource sharing based CUs capacity, and video segment transmission. The RSA optimization problems and solutions are presented in Sect. 3. We show the simulation results with detailed performance evaluation in Sect. 4. Finally, Sect. 5 is dedicated to concluding the paper.

2 System Models

2.1 VASs over MHMP in Dense D2D 5G Networks

In this paper, we consider the VASs over MHMP in a dense D2D 5G network as shown in Fig. 1. Thanks to dense D2D users in 5G networks, we assume that there are at least K DHs that have cached the requested video consisting of S segments ($S \leq K$). We also assume that there are K paths established from the K DHs to the DR by using [19,24], here the path k has H_k D2D hops. The D2D users are randomly located and modeled as 2-D homogeneous Poisson point process (PPP) in a circular cell with intensity λ_D [25,26]. In the system, there are N CUs ($N \geq K$) that share their downlink resources with H_k D2D hops in the path k. An arbitrary CU can share its downlink resource with only one D2D hop in a path, but with up to K D2D hops in K paths. The transmission over the D2D hop h_k in path k is done by reusing the downlink resource shared by the CU n optimally selected from N CUs such that the average capacity of the CUs is maximized. Finally, S segments of the requested video are optimally allocated to K paths for sending so as to minimize the reconstructed distortion of received video at the DR.

2.2 Downlink Resource Sharing Based CUs Capacity

In our aforementioned downlink sharing scheme, the CU n suffers interference from the transmitters of up to K D2D hops in K paths. Therefore, the signal to interference plus noise ratio (SINR) at the CU n is given by

$$SINR_C^n = \frac{P_M G_{M,C}^n}{N_0 + \sum_{k=1}^{K} P_D^{h_k} G_{D,C}^{n,h_k}}, \tag{1}$$

where P_M and $P_D^{h_k}$ are the transmission powers of the MB and the transmitter of the D2D hop h_k in the path k; N_0 is the power of additive white Gaussian noise (AWGN); $G_{M,C}^n$ and $G_{D,C}^{n,h_k}$ are the channel gains from the MB and the transmitter of the D2D hop h_k to the CU n, which are modelled as an exponential power fading coefficient with unit mean ($\sim$exp(1)) and a standard power law path loss function with path loss exponent η [25,26].

The problem is that how to allocate the downlink resource of the CU n to the D2D hop h_k, h_k=1, 2, ..., H_k, such that the total interference effect on the CU n is minimized, i.e., gaining the highest SINR at the CU n. To do so, we add a downlink resource sharing allocation (RA) index v_{n,h_k} to (1) to indicate that if the CU n agrees to share ($v_{n,h_k} = 1$) with the D2D hop h_k or not ($v_{n,h_k} = 0$). Therefore, Eq. (1) is re-written as

$$SINR_C^n = \frac{P_M G_{M,C}^n}{N_0 + \sum_{k=1}^{K} \sum_{h_k=1}^{H_k} v_{n,h_k} P_D^{h_k} G_{D,C}^{n,h_k}}. \tag{2}$$

Based on Shannon-like capacity, the capacity delivered to the CU n and the average capacity per each CU are respectively given by

$$C_C^n = W \log_2(1 + SINR_C^n) \tag{3}$$

and

$$\overline{C} = \frac{1}{N} \sum_{n=1}^{N} C_C^n, \tag{4}$$

where W is the system bandwidth.

In this paper, $\overline{C}$ in (4) is maximized by finding the optimal values of v_{n,h_k}. This so-called RA optimization problem and solution are introduced in the next section.

2.3 Video Segment Transmission

In the SA optimization problem, S segments of the requested video are allocated to K paths such that the reconstructed distortion of the received video at the DR is minimized. To do so, we take into account the RD based video packetization scheme at the DHs and the multi-hop lossy wireless environment analysis, which are presented below.

RD Based Video Packetization Scheme: Aiming at providing the highest data protection strategy and the robustness over the diverse characteristics of the MHMP wireless environment, we exploit the benefits of scalable extensions of high efficiency video coding (SHVC) to packetize each segment of the requested video into M descriptions for transmission by using layered multiple description coding with embedded forward error correction (LMDC-FEC) [23,27–34]. The most important characteristic of SHVC based LMDC-FEC is that the reconstructed distortion of the received segment is more reduced for higher playback quality if more descriptions are correctly received without considering the orders of the received descriptions.

By further applying the RD model given in [30,31] to SHVC, if the segment s has m out of M descriptions received correctly, this segment is decoded for playing back at the rate R_s^m corresponding to the reconstructed distortion $D_s(R_s^m)$. The relationship between rate R_s^m (measured in Kbps) and the reconstructed distortion $D_s(R_s^m)$ follows a decaying exponential function given by

$$D_s(R_s^m) = \gamma_s (R_s^m)^{\beta_s}, \tag{5}$$

where γ_s and β_s are the independent parameters found by analysing the experimental characteristic of the segment s.

Description Multi-hop Delay: A description of the segment s is lost over the path k if it does not arrive in time at the DR for playing back. Following [35,36] and ignoring the total processing delay, given a delay threshold $\tau_{s,k}$, the loss probability of a description of the segment s is expressed as

$$L_D^{s,k} = \int_{\tau_{s,k}}^{\infty} \frac{\mu_k}{\Gamma(H_k+1)} (\mu_k t)^{H_k} e^{-\mu_k t} dt, \tag{6}$$

where the delay threshold $\tau_{s,k}$ and the average waiting delay per hop $1/\mu_k$ are respectively given by

$$\tau_{s,k} = \kappa \sum_{h_k=1}^{H_k} t_{h_k} + \frac{(s-1)F}{Sf} \tag{7}$$

and

$$\frac{1}{\mu_k} = \frac{\sum_{h_k=1}^{H_k} t_{h_k}}{H_k}, \tag{8}$$

where $\kappa \geq 1$ is the startup delay coefficient, t_{h_k} is the waiting delay of hop h_k, and F and f are the number of frames and the frame rate of the considered video, respectively.

Description Multi-hop Transmission Error: In addition, a description of a segment is lost over the path k due to transmission error. After finding which CUs share their downlink resources with which D2D hops in all K paths, let P_{h_k} be the outage probability of the hop h_k, if a description of a segment is sent over the path k, the loss probability of this description is expressed as

$$L_T^k = 1 - p_k \prod_{h_k=1}^{H_k} (1 - P_{h_k}), \tag{9}$$

where p_k is the probability that the video has been cached in the DH k. By following [25,26] in which N_0 is negligible, given a threshold of capacity (i.e, bit rate) C_{th} for reliable communications, and assuming that the statistical model of channel over the hop h_k is Rayleigh fading, P_{h_k} can be computed as

$$P_{h_k} = P\{C_D^{h_k} < C_{th}\} = 1 - \texttt{exp}\Big\{ - \xi_{h_k} \Big[\lambda_M \Big(\frac{P_M}{P_D^{h_k}} \Big)^{\frac{2}{\eta}} + \lambda_D \Big] \Big\}, \tag{10}$$

where $\xi_{h_k} = \sum_{n=1}^{N} v_{n,h_k} \pi d_{h_k}^2 \Gamma(1+\frac{2}{\eta})\Gamma(1-\frac{2}{\eta})\big(2^{\frac{C_{th}}{W}} - 1\big)^{2/\eta}$, d_{h_k} is the distance from the transmitter to the receiver of the hop h_k, and $C_D^{h_k}$ is the capacity at the receiver of the D2D hop h_k coming from its corresponding signal-to-interference-plus-noise ratio $SINR_D^{h_k}$, expressed as

$$SINR_D^{h_k} = \frac{\sum_{n=1}^{N} v_{n,h_k} P_D^{h_k} G_{D,D}^{n,h_k}}{N_o + P_M G_{M,R}^n + \sum_{n=1}^{N} \sum_{l=1,l\neq k}^{K} \sum_{h_l=1}^{H_l} v_{n,h_l} P_D^{h_l} G_{D,R}^{n,h_l}} \tag{11}$$

and

$$C_D^{h_k} = W \log_2(1 + SINR_D^{h_k}). \tag{12}$$

Description Loss Probability: So far, a description of the segment s is lost if it arrives at the DR later than the threshold or it is not received correctly at the DR due to transmission error. The loss probability of a description of the segment s is computed as

$$L_{s,k} = L_T^k + (1 - L_T^k) L_D^{s,k}. \tag{13}$$

Finally, the probability that m out of M descriptions of the segment s are correctly received over the path k is given by

$$P_{M,m}^{s,k} = \binom{m}{M} (1 - L_{s,k})^m (L_{s,k})^{M-m}. \tag{14}$$

Reconstructed Distortion: Based on the aforementioned analysis of the RD based video packetization scheme and the multi-hop lossy wireless environment, we further take into account the segment allocation index $u_{s,k}$ to indicate that if the segment s is selected to be sent over the path k ($u_{s,k} = 1$) or not ($u_{s,k} = 0$) so as to minimize the average reconstructed distortion of received video at the DR. Consequently, the average reconstructed distortion of the received video at the DR is computed as

$$\overline{D} = \sum_{s=1}^{S} r_s \sum_{k=1}^{K} u_{s,k} \sum_{m=0}^{M} P_{M,m}^{s,k} D_s(R_s^m), \tag{15}$$

where r_s, which is the access rate (popularity) of the segment s representing the users' behavior, is modelled by following Zipf-like distribution [37], given by

$$r_s = \frac{s^{-\alpha}}{\sum_{s=1}^{S} s^{-\alpha}}, \tag{16}$$

here α is the skewed access rate among different segments of the considered video. It means that if $\alpha = 0$, all segments have the same access rate, while the higher value of α yields the higher skewed access rate among different segments.

3 RSA Optimization Problems and Solutions

In the RA problem, it is to maximize the average capacity $\overline{C}$ per each CU that shares its resource for MHMP D2D communications. The optimal values of v_{n,h_k} are found such that the interference effect on the CUs caused by the transmitters of D2D hops is minimized. In addition, we further take into account the constraints of $\sum_{h_k=1}^{H_k} v_{n,h_k} \leq 1$ (each CU can share with up to one D2D hop in each path), $\sum_{n=1}^{N} v_{n,h_k} = 1$ (each D2D hop in a path can be shared by only one CU), and $\sum_{n=1}^{N}\sum_{h_k=1}^{H_k} v_{n,h_k} = H_k$ (all CUs can share up to H_k D2D hops in each path). The RA problem is formulated as follows:

$$\max_{v_{n,h_k}} \overline{C} \tag{17}$$

$$s.t. \begin{cases} \sum_{h_k=1}^{H_k} v_{n,h_k} \leq 1, n = 1, 2, ..., N, k = 1, 2, ..., K, \\ \sum_{n=1}^{N} v_{n,h_k} = 1, k = 1, 2, ..., K, \\ \sum_{n=1}^{N}\sum_{h_k=1}^{H_k} v_{n,h_k} = H_k, k = 1, 2, ..., K. \end{cases} \tag{18}$$

After solving (17) and (18), all the D2D hops in K paths are established for video streaming from the DHs to the DR. In the SA problem, the optimal values of $u_{s,k}$ are found to yield the optimal matching allocation between the access rate r_s and the RD of the segment s induced lossy characteristic of the path k such that the average reconstructed distortion $\overline{D}$ of the received video at the DR is minimized. In addition, because we have S segments, i.e., $S \leq K$, sent over K paths, there have some paths that are not used. We further take into account the constraints of $\sum_{s=1}^{S} u_{s,k} \leq 1$, $\sum_{k=1}^{K} u_{s,k} = 1$, and $\sum_{s=1}^{S}\sum_{k=1}^{K} u_{s,k} = S$ to ensure that each path can send up to one segment, each segment is sent over only one path, and K paths must send all S segments. The SA problem is formulated as follows:

$$\min_{u_{s,k}} \overline{D} \tag{19}$$

$$s.t. \begin{cases} \sum_{s=1}^{S} u_{s,k} \leq 1, k = 1, 2, ..., K, \\ \sum_{k=1}^{K} u_{s,k} = 1, s = 1, 2, ..., S, \\ \sum_{s=1}^{S}\sum_{k=1}^{K} u_{s,k} = S. \end{cases} \tag{20}$$

Both the RA and SA optimization problems can be solved by using exhaustive binary matrix search, in which finding optimal values of v_{n,h_k} and $u_{s,k}$ is actually finding the optimal matrices $\{V^*_{N\times H_1}; V^*_{N\times H_2}; ...; V^*_{N\times H_K}\}$ and $U^*_{S\times K}$ by searching the following binary matrix spaces:

$$\mathcal{V} = \{V^1_{N\times H_1}, V^2_{N\times H_1}, ..., V^{2^{N\times H_1}}_{N\times H_1}; V^1_{N\times H_2}, V^2_{N\times H_2}, ..., V^{2^{N\times H_2}}_{N\times H_2}; \\ ...; V^1_{N\times H_K}, V^2_{N\times H_K}, ..., V^{2^{N\times H_K}}_{N\times H_K}\} \tag{21}$$

and

$$\mathcal{U} = \{U^1_{S\times K}, U^2_{S\times K}, ..., U^{2^{S\times K}}_{S\times K}\}. \tag{22}$$

4 Performance Evaluation

The system parameters setting is given in Table 1. Furthermore, the distance of D2D hops, distance from D2D transmitters to the CUs, and distance from the MB to the CUs and the D2D receivers, are respectively in the ranges of [1, 10] m, [1, 50] m, and [300, 1500] m. The system is covered by a circular area with radius of 1500 m, and thus $\lambda_M = 0.14147 \times 10^{-6}$ and $\lambda_D = 1.9806 \times 10^{-6}$. We evaluate the performance of the proposed **RSA** (i.e., **RA** and **SA**) by comparing it to the other two benchmarks without RSA, namely Average (**Ave**) and Minimum (**Min**). In **Ave**, the capacity of the CUs and the reconstructed distortion of received video are averaged over the number of feasible solution sets of $\mathcal{V}$ and the number of feasible solutions of $\mathcal{U}$ that satisfy (18) and (20). Meanwhile in **Min**, the capacity of the CUs and the reconstructed distortion of received video are computed by finding the worst feasible solution set of $\mathcal{V}$ and the worst feasible solution of $\mathcal{U}$ that cause the average capacity of CUs and the playback quality at the DR minimum.

Table 1. Parameters setting

Symbols	Specifications
S	3 segments
K	4 paths
H_k	{1, 2, 3, 4} D2D hop(s)
N	5 CUs
W	10 MHz
P_M	10 W
p_k	{1, 1, 1, 1}
M	32 descriptions
C_{th}	1 bps
γ_s	{10, 20, 30}
β_s	{−0.5, −0.75, −1}
η	4
F	300 frames
f	24 frames/s
R_s^M	3000 Kbps (full rate of each segment)
κ	1
t_{h_k}	Randomly distributed in the range of [0.0002, 0.002] s
$P_D^{h_k}$	Randomly distributed in the range of [0.1, 0.5] W
N_0	10^{-13} W

We first evaluate the capacity performance of the **RA**, **Ave**, and **Min** versus the number of paths by changing K from 1 to 5. As shown in Fig. 2, if the number of paths increases, the CUs suffer from higher interference impacts caused by

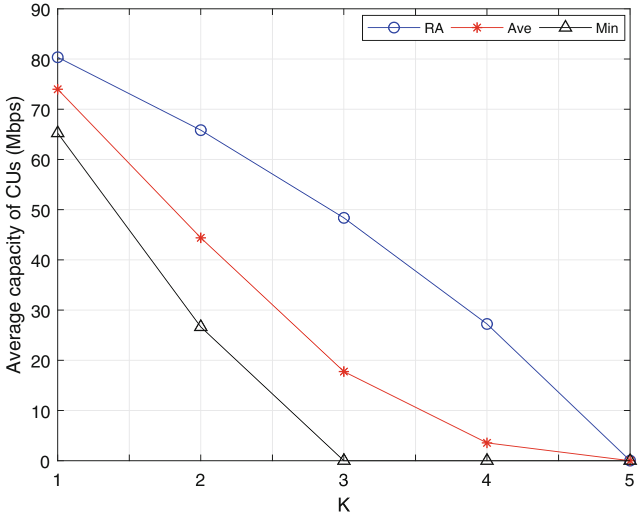

Fig. 2. Average capacity of CUs versus number of paths.

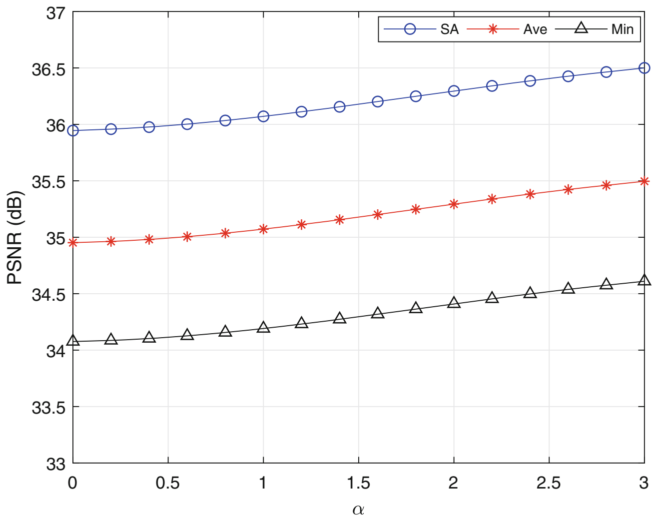

Fig. 3. Quality of received video at DR versus skewed access rate of segments.

dense D2D hops, and thus the average capacity of CUs decreases, even approximately to zero when $K = 5$. In comparison, the **RA** outperforms the **Ave** and **Min**. It is noted that the number of paths for MHMP D2D communications is carefully selected to guarantee the CUs high quality of service. In addition, if we do not optimally allocate the downlink resource sharing-receiving pairs between

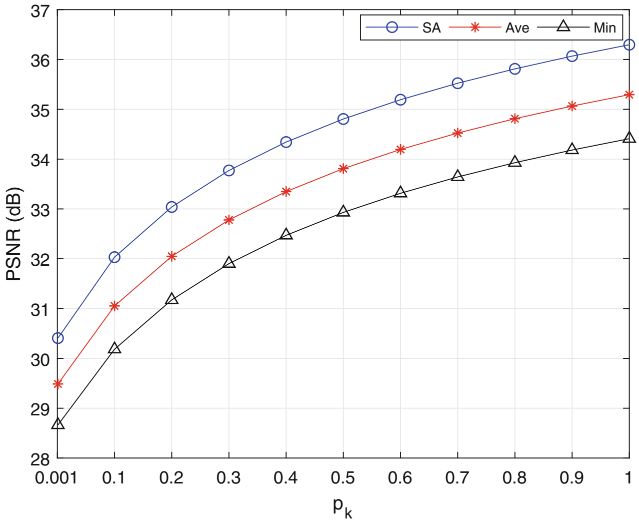

Fig. 4. Quality of received video at DR versus caching probability.

the CUs and the D2D hops, the capacity of the CUs may be equal to the common value (the **Ave** case) or even the worst value (the **Min** case).

Next, we evaluate the performance of the **SA**, **Ave**, and **Min**, i.e., measured in peak signal-to-noise ratio (PSNR), versus the skewed access rate (α) among different segments. The results in Fig. 3 show that the higher skewed access rate the segments have, the higher performance the system gains. It means that exploiting the skewed access rate to serve the most popular segments rather than the less popular ones can improve the system performance. Obviously, the **SA** provides higher PSNR than the **Ave** and **Min** do.

Finally, Fig. 4 plots the PSNR performance of the **SA**, **Ave**, and **Min** versus the probability (p_k) that the considered video has cached in the DH k. In this case, it is meaningless if $p_k = 0$, so we change p_k from 0.001 to 1. It is easy to observe that the system provides higher PSNR if p_k increases and the proposed **SA** is always better than the **Ave** and **Min**, i.e., up to 1 dB and about 2 dB higher than **Ave** and **Min**, respectively.

5 Conclusion

In this paper, we have proposed a downlink resource sharing and segment allocation (RSA) optimization solution for high performance of video streaming applications and services over multi-hop multi-path (MHMP) in dense D2D 5G networks. In particular, the RSA can exploit the dense characteristic of D2D users with cached video and the available downlink resources of the CUs to establish a MHMP video streaming session that can guarantee the CUs maximum average capacity. In addition, by considering the characteristics of the video, the users' behavior, and the multi-hop lossy wireless environment, the RSA can provide the D2D requester with minimum reconstructed distortion of the received video for high playback quality.

Acknowledgement. This research is funded by Vietnam National Foundation for Science and Technology Development (NAFOSTED) under grant number 102.04-2018.308.

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