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Rate-User-Perceived-Quality Aware Replication Strategy for Video Streaming over Wireless Mesh Networks

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Abstract

In this research, we consider the replication strategy for the applications of video streaming in wireless mesh networks (WMNs). In particular, we propose a closed-form of optimal replication densities for a set of frames of a video streaming by exploiting not only the skewed access probability of each frame but also the skewed loss probability and skewed encoding rate-distortion information. The simulation results demonstrate that our method improves the replication performance in terms of user-perceived quality (UPQ) which includes: 1) minimum average maximum reconstructed distortion for high peak signal-to-noise ratio (PSNR), 2) small reconstructed distortion fluctuation among frames for smooth playback, and 3) reasonable average maximum transmission distance for continuous playback. Furthermore, the proposed strategy consumes smaller storage capacity compared to other existing optimal replication strategies. More importantly, the effect of encoding rate is carefully investigated to show that high encoding rate does not always gain high performance of replication for video streaming.

Keywords: Rate-distortion, replication strategy, user-perceived quality, wireless mesh networks

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1. Introduction

Wireless mesh networks (WMNs) [1] have been rapidly playing an important role in practical and commercial solutions of broadband wireless Internet for serving users a large variety of application scenarios. Besides, recent years have witnessed the blooming users' demands that are attracted by video streaming applications. The fast increasing number of users with huge size videos and the existence of dynamically varying and limited resources as well as relatively unreliable connectivity in wireless infrastructure make it challenging for WMNs to deliver video streaming at high user-perceived quality (UPQ). More importantly, the UPQ implies many subjective and complicated measures that are used to evaluate the satisfaction of users when they are watching a video streaming. The three main aspects of high UPQ include: 1) high peak signal-to-noise ratio (PSNR) represented by minimum average maximum reconstructed distortion of received video streaming, 2) smooth playback defined by minimum reconstructed distortion fluctuation among received video frames, and 3) continuous playback based on the punctual receive of video frames. On the other hand, in the view of network resources-saving, video streaming applications should use the bandwidth of network efficiently as well as consume small storage capacity of network.

To overcome the mentioned problems of video streaming applications in WMNs, replication strategies have been studied to support the users in retrieving video streaming from replicated mesh routers within the backbone of WMNs instead of from the Internet through gateways. Specifically, when a gateway observes that a video streaming from the Internet is accessed with a high rate, the video segments are proactively replicated in some indicated mesh routers, closer to the users, for future use. In this way, the effect of dynamically varying properties of wireless network environment is reduced for high UPQ. Additionally, the gateway bottleneck is mitigated by sharing workload with the mesh routers so that the use of bandwidth resource is spread over the backbone of WMNs in an equal and efficient manner, and the data accessibility is improved. The remaining problem is that we should consider the trade-off between storage capacity requirement (SCR) for replicating and UPQ. Using larger SCR of network to place more replicas with higher densities for higher UPQ or vice versa is always the biggest challenge to replication strategies.

Most of the pioneering replication strategy approaches are to improve data accessibility, for example: reference [2], [3], [4] and [5] in wireless ad hoc networks (WAHNs), [6] in wireless peer-to-peer networks (WP2PNs), [7], [8], [9] and [10] in video on demand (VoD) systems, and [11] and [12] in WMNs. Different strategies are distinguished from each other based on evaluating their data accessibility performance. As we discussed, however, data accessibility is not proper enough in replication of video streaming context, in which the users expect high UPQ while consuming small SCR of network.

Motivated by all of the above discussions, in our first work [13], a combinatorial analysis was proposed to express three crucial metrics of UPQ as well as SCR for replicating. And then, in [14], a cross-layer design was adopted to optimize UPQ at the application layer by solving a nonlinear constrained optimization problem for an optimal video re-encoding scheme, without concerning SCR.

In this paper, different from our previous works [13][14], we improve UPQ by solving an unconstrained optimization problem for a closed-form of optimal replication density using the law of equi-marginal utility and carefully investigate SCR. Based on this, we achieve: 1) minimum average maximum reconstructed distortion for high PSNR, 2) small reconstructed distortion fluctuation for smooth playback, 3) reasonable average maximum transmission distance (AMTD) from the replicated mesh routers to the users for continuous playback, i.e., all for high UPQ; and 4) small replication SCR for saving the resource of network. Furthermore, we carefully investigate the effect of encoding rate on the performance of replication for video streaming to demonstrate that high encoding rate clearly consumes large SCR but does not certainly achieve high UPQ. Especially, for this method, solving the nonlinear constrained optimization problem and re-encoding the video streaming as in [14] are not necessary so that the computation/processing tasks at the gateways are reduced significantly.

The rest of this paper is organized as follows. In Section 2, we discuss some related work. Section 3 presents the problem formulations related to UPQ and SCR. In Section 4, we propose a method for a closed-form of optimal replication density, and briefly introduce the implementation of replication at the gateways of WMNs. We show the performance evaluations to demonstrate the advantages of our method compared to other replication strategies in Section 5. Finally, the conclusions are stated in Section 6.

2. Related Work

Many researchers have proposed replication strategies to provide users with high data accessibility. These strategies might meet continuous playback requirement, but could neither satisfy the full aspects of high UPQ nor consume small SCR in video streaming applications. This context will be made clear by investigating some typically existing replication strategies as follows.

In WAHNs with environment of high dynamic and frequent disconnection, H. Yu *et al.* [2] proposed distributed hash table replication by which all mobile nodes are organized into non-overlapping clusters. At the same time, a two-level distributed replica information directory on the cluster heads is established in order to mitigate the delay of query and update messages. Unlike the objective in [2], the authors in [3] introduced a method to find out a near optimal proportional relationship between the number of replicas of a video clip and the product of its display bandwidth requirement and its access probability so as to maximize the number of simultaneous displays in the system. However, the objective metrics in both [2] and [3] do not directly have effect on the three main aspects of high UPQ (i.e., high PSNR, smooth playback, and continuous playback), nor the SCR, which are used to evaluate the performance of replication strategies in video streaming applications.

Other important replication solutions to enhance data accessibility for WAHNs include [4] and [5]. [4] presented several topology and access probability of segment-aware replication strategies to discover and retrieve replicas of video segments with minimum number of hops. In [5], to deal with the problem of frequent network partition causing data accessibility of WAHNs to be lower than that of traditional fixed networks, three main replica allocation methods, i.e., Static Access Frequency (SAF), Dynamic Access Frequency and Neighborhood (DAFN), and Dynamic Connectivity-based Grouping (DCG), and their extensions were proposed. These studies might satisfy continuous playback, but a high UPQ requirement could not be ensured because PSNR and smooth playback were not considered. Besides, the performance of replication was not completely evaluated without regarding SCR.

In the research field of WP2PNs, the authors in [6] proposed a novel replication technique especially used for continuous media in order to enhance startup latency and minimize total storage space. However, this technique assumes that the first video segments are more urgent than the rear ones, meanwhile the users may move forward or backward for their interested segments randomly. So, it is not feasible to be applied to the real context of video streaming applications. Furthermore, enhancing startup latency is not adequate for high UPQ.

Related to a particular video streaming application, [7], [8], [9] and [10] introduced many different replication techniques to improve the performance of VoD systems. A. E. Baert *et al.* [7] formulated a nonlinear integer constrained optimization problem in replication. Then, this optimization problem was solved to minimize average download time expected by users. Unlike [7], the authors in [8] tried to deal with the problems of how to optimally generate a number of replicas of a video placed in the peers so that the availability of video is maximized to achieve higher success playback probability. More interestingly, besides maximizing the availability of videos [8], [9] proposed a novel optimal prefix replication strategy in order to maximize the client request-servicing rate and to minimize the initial startup latency as well as the client rejection ratio. In the latest research, by exploiting the fact that the users accessing a video follow Zipf-like distribution [15], the authors in [10] presented a video allocation algorithm to balance workload in servers and thus service latency can be reduced. Clearly, we can see the problem that all considered performance metrics of the proposed techniques in VoD system do not directly reflect the subjective human perception [16], the most important application metric, which can be characterized by the three aspects of UPQ as we mentioned. This problem accompanied by not considering SCR evaluation limits these techniques to be deployed in such VoD systems.

Nevertheless, in the field of WMNs, replication strategies have not been studied well. In [11], the objective of content and service replication strategies is to determine an optimal number of replicas while minimizing average cost to access an object in 2-D mesh networks based on the access probability of the object. Although these replication strategies are used for general data, they ensure minimum AMTD for continuous playback when applied to video streaming applications [14]. But, the other two metrics of UPQ as well as SCR were not considered in [11]. [12] is an extension case study of [6] by taking into account the frequent online/offline behavior of users and the access probability of the videos. Therefore, the problem of providing users with high PSNR and smooth playback have not been solved yet.

3. Problem Formulations

In this section, we introduce the problem formulations to express some important metrics associated with UPQ and SCR, which enable us to propose optimal replication density in our strategy. To do so, in replication scenario, we first define a key metric: the maximum transmission distance.

3.1 Maximum Transmission Distance

Maximum transmission distance between the replicated mesh routers of frame i and the users, i.e., the radius of replication of frame i, $H_i^{\max}$ (hops), is inversely proportional to the square-root of replication density of frame i, r_i, under the aggregate capacity constraint $\sum_{i=1}^{n} r_i = 1$. Specifically, we have

$$H_i^{\max} = \frac{\Omega}{\sqrt{r_i}} \tag{1}$$

where Ω is a predefined constant.

It is clearly observed that if the replication density of a frame is increased by four times, the maximum transmission distance from the replicated points of this frame to the users is decreased by half. The meaning of using $H_i^{\max}$ is that the distributed implementation of replication strategy tries to place one replica of frame i within the radius of $H_i^{\max}$ hops. Especially, when $H_i^{\max} = 0$, frame i is replicated in all mesh routers of WMNs. Hereafter, we alternately use both the radius of replication and the replication density.

3.2 Average Maximum Reconstructed Distortion

For the first metric of UPQ, high PSNR, we aim at minimizing average maximum reconstructed distortion (AMRD) of received video streaming which comes from source distortion model under the effect of transmission error as follows.

Practically, the source distortion can be obtained at a certain rate by using rate-distortion (RD) model when encoding a video streaming. For the purpose of rate control (sometimes optimal rate allocation), different RD models have been proposed and efficiently adopted to corresponding video encoding standards, e.g., MPEG-2, H.263, MPEG-4, or H.264/AVC. Among these standards, although the RD model of H.264/AVC has been more widely used due to its higher performance in terms of RD optimization, the optimal rate allocation algorithm is very complicated [17][18]. Thus, in this research, we utilize the RD model of Fine Granularity Scalability (FGS) encoded sequences following the MPEG-4 standard for simplicity.

Let us take FGS sequence introduced in [19] and [20] as an example. There are two kinds of stream in the FGS-encoded sequence, i.e., a non-scalable base layer (BL) and a scalable enhancement layer (EL). The BL provides basic quality and the EL contributes additional quality which is determined by the number of bits and the content of frames. In other words, for each frame, the more bits (or sometimes higher rate) the EL is encoded, the higher reduction in distortion and thus the lower source distortion the video streaming is decoded. This is also known as RD model of video sequence.

Following the linear RD model introduced in [21] and using Microsoft MPEG-4 Video Reference Software [22], we readily obtain a mutual relationship between the rate of EL and the source distortion of each frame corresponding to the content of frame. As an example, the RD models and contents of the 100−th and 200−th frames of common international format (CIF) Mobile sequence are illustrated in **Fig. 1**. Specifically, at a given rate, f_i, the source distortion of the *i*-th frame is described in the form of

$$d_i(f_i) = d_i^{bl} - \Delta d_i^{el}(f_i) \tag{2}$$

where d_i^{bl} represents the distortion of the *i*-th frame when it is decoded without EL frame, while if the EL frame is correctly decoded at the rate f_i, the source distortion $d_i(f_i)$ of this frame is decreased by an amount of reduction in distortion $\Delta d_i^{el}(f_i)$. $\Delta d_i^{el}(f_i)$ is actually the encoding RD information of the *i*-th frame.

In this paper, similarly as in [21], because the BL frames are of small size and play an important role in reconstructed quality playback, we assume that they are sent without loss and correctly decoded at the users by using forward or backward error correction scheme (if the roundtrip time is relatively small). Therefore, we only consider the EL frames to analyze the reconstructed distortion of received video streaming. Let E_i be the per-hop loss probability of the *i*-th frame, (2) becomes

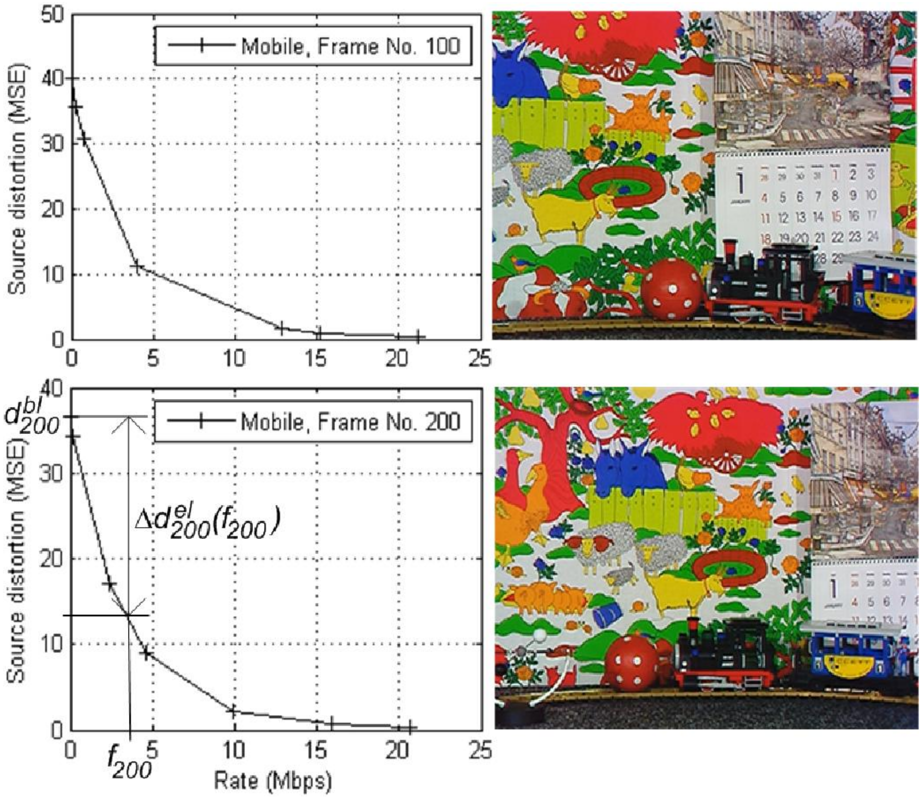

Fig. 1. Linear RD models and contents of the 100−th and 200−th frames of CIF Mobile sequence

$$d_i^r\left(f_i, E_i, H_i^{\max}\right) = d_i^{bl} - \Delta d_i^{el}(f_i)(1-E_i)^{H_i^{\max}} \tag{3}$$

It should be noted that (3) is exactly the maximum reconstructed distortion of the *i*-th frame after tolerating a maximum transmission distance, $H_i^{\max}$ hops, to be received at the users.

By taking into account intra popularity distribution of the video streaming, the users may randomly move backward or forward for their interested playback positions while viewing the video. Thus, each frame of the video has its own intra popularity or access probability, p_i. It can be deduced that the AMRD of received video streaming is calculated as

$$\overline{D} = \sum_{i=1}^{n} p_i d_i^r\left(f_i, E_i, H_i^{\max}\right) = \overline{D_{bl}} - \sum_{i=1}^{n} p_i \Delta d_i^{el}(f_i)(1-E_i)^{H_i^{\max}} \tag{4}$$

where $\overline{D_{bl}} = \sum_{i=1}^{n} p_i d_i^{bl}$, and *n* is the number of frames of the video.

Assuming that E_i is much less than 1, (4) or the so-called objective function for high PSNR asymptotically converges to

$$\overline{D} \approx \overline{D_{bl}} - \overline{\Delta D_{el}} + \sum_{i=1}^{n} p_i E_i \Delta d_i^{el}(f_i) H_i^{\max} \tag{5}$$

where $\overline{\Delta D_{el}} = \sum_{i=1}^{n} p_i \Delta d_i^{el}(f_i)$.

3.3 Reconstructed Distortion Fluctuation

In case of the second metric of UPQ, that is smooth playback, our objective is to reduce the reconstructed distortion fluctuation among the frames of received video streaming. The reason motivates us to consider this metric when proposing optimal replication density is that if the more popular frames of the video are replicated with higher densities, the reconstructed distortion of such these frames is much less than the rear ones. This diverse problem of reconstructed distortion in turn causes the received video rough, or not smooth to be seen at the users. The smooth playback can be represented by computing the standard deviation of reconstructed distortion of received video frames as below

$$\sigma_d = \sqrt{\sum_{i=1}^{n} p_i \left[d_i^r (f_i, E_i, H_i^{\max}) - \overline{D} \right]^2} \tag{6}$$

3.4 Average Maximum Transmission Distance

With the last metric of UPQ, besides providing the users with minimum AMRD for high PSNR and small reconstructed distortion fluctuation for smooth playback, optimal replication strategy should ensure that every frame of a video streaming arrives in time for continuous playback. Although continuous playback criterion is a complex function of many parameters such as guaranteed bandwidth per hop, delay per hop, transmission distance (hop-count), etc., it can be basically characterized by AMTD for simplicity. The AMTD can be obtained by

$$\overline{H} = \sum_{i=1}^{n} p_i H_i^{\max} \tag{7}$$

3.5 Storage Capacity Requirement

As we discussed, replication strategy should not ignore the problem of evaluating the consumption of network resources in terms of SCR. Considering a grid topology WMNs with *N* mesh routers and given replication densities of all video frames, there are $2\left(H_i^{\max}\right)^2 + 2H_i^{\max} + 1$ mesh routers within the radius of $H_i^{\max}$ hops from an arbitrary center one. Thus, the SCR for replicating a video streaming with *n* frames is given by [6]

$$S_c = N \sum_{i=1}^{n} \frac{s_i}{2\left(H_i^{\max}\right)^2 + 2H_i^{\max} + 1} \tag{8}$$

where s_i is byte-size of the *i*-th frame.

4. Proposed Optimal Replication Strategy

In this section, we first propose a method for solving an unconstrained optimization problem in order to improve UPQ. And then, a closed-form of optimal replication density is given by applying Zipf-like distribution. Finally, distributed implementation for replication strategy is briefly introduced.

4.1 Optimal Replication Density

Mathematically, based on the mentioned expressions of UPQ and SCR, we can formulate a nonlinear constrained optimization problem in which (5) is considered as the objective function while the metrics in (6), (7), and (8) are used as constraints. However, for simplicity but efficiency, we only focus on minimizing $\overline{D}$ (5) by determining optimal replication density for each frame without any constraints. And then, we evaluate the other performance metrics, e.g., reconstructed distortion fluctuation (6), AMTD (7), and SCR (8) of the proposed method by comparing to other existing optimal replication strategies.

To the best of our knowledge, in most of pioneering replication strategies, optimal replication densities for all segments of a video streaming are generated to satisfy some specific objectives. These optimal replication densities are often given in two general forms. The first one is radius of replication of the *i*-th segment, $H_i^{\max}$, and the other is replication density, r_i, of the *i*-th segment as mentioned in (1). Examples include: 1) $H_i^{\max}$ is determined to minimize startup latency strategy in [6] and [12]; 2) Shudong Jin [11] proved that the replication density, r_i, for the *i*-th most popular segment must be proportional to $p_i^{2/3}$ so as to achieve minimum access cost (MAC); and 3) in [23], for a minimum value of query cost (MQC), the replication density, r_i, should be proportional to $p_i^{1/2}$, etc.

Unlike [6], [11], [12] and [23], our objective is to minimize AMRD, $\overline{D}$, by determining optimal replication density, r_i, for frame *i*. The main idea is that if frame *i* is accessed with higher probability (p_i), suffers higher per-hop loss probability (E_i), and contributes higher reduction in distortion ($\Delta d_i^{el}(f_i)$) to the reconstructed video streaming quality; the maximum transmission distance from its replicated points to the users, $H_i^{\max}$, should be shorter. In other words, frame *i* should be replicated with higher density, r_i. Particularly, we have the following result:

Theorem 1: To minimize AMRD, $\overline{D}$, the replication density of the *i*-th frame of a video streaming is proportional to $(p_i e_i d_i^{el})^{2/3}$.

where
$$e_i = \frac{E_i}{\sum_{i=1}^{n} E_i} \tag{9}$$

and
$$d_i^{el} = \frac{\Delta d_i^{el}(f_i)}{\sum_{i=1}^{n} \Delta d_i^{el}(f_i)} \tag{10}$$

Proof: From (5), the problem of minimizing AMRD, $\overline{D}$, is now equivalent to minimizing the amount of

$$\Delta D = \sum_{i=1}^{n} p_i E_i \Delta d_i^{el}(f_i) H_i^{\max} \tag{11}$$

or we need to minimize

$$\Delta d = \Omega \sum_{i=1}^{n} \frac{p_i e_i d_i^{el}}{\sqrt{r_i}} \tag{12}$$

This problem can be solved by using the law of equimarginal utility which is usually applied to economics as follows.

Let the utility function $U_i(r_i) = -p_i e_i d_i^{el} / \sqrt{r_i}$, we obtain the marginal utility function

$$U_i^{'}(r_i) = \frac{1}{2} p_i e_i d_i^{el} r_i^{-3/2} \tag{13}$$

It can be observed that $U_i^{'}(r_i)$ is a monotone decrease function of r_i and this property allows us to adopt the law of equi-marginal utility. Consequently, from (13), let $U_i^{'}(r_i) = U_j^{'}(r_j)$, we have

$$r_i \propto (p_i e_i d_i^{el})^{2/3} \tag{14}$$

Now, Zipf-like distribution [15] is applied to find out the closed-form of optimal replication density. With Zipf-like distribution, the access probability of the *i*-th frame, p_i , is proportional to $i^{-\alpha}$. More precisely, this is written as

$$p_i = \frac{i^{-\alpha}}{\sum_{i=1}^{n} i^{-\alpha}} \tag{15}$$

By replacing (14) with (9), (10) and (15), and because of the constraint $\sum_{i=1}^{n} r_i = 1$, we finally obtain the closed-form of optimal replication density to minimize AMRD as below

$$r_i = \frac{i^{-2\alpha/3}\left(E_i \Delta d_i^{el}(f_i)\right)^{2/3}}{\sum_{i=1}^{n}\left[i^{-2\alpha/3}\left(E_i \Delta d_i^{el}(f_i)\right)^{2/3}\right]} \tag{16}$$

And the minimum value of AMRD, $\overline{D}$, can be readily calculated by substituting (5) with (1), (15), and (16).

It is interesting that during generating optimal values of r_i for minimum AMRD, the reconstructed distortion fluctuation among frames is also kept balanced for smooth playback.

As we can observe from (5), the reconstructed distortion fluctuation depends on the amount $\left[p_i E_i \Delta d_i^{el}(f_i) H_i^{\max}\right]$ of every frame. If this amount is much skewed among frames, the distortion fluctuation is high. However, according to the optimal result in (14), if the product of p_i, e_i (or E_i), and d_i^{el} (or $\Delta d_i^{el}(f_i)$) of the i-th frame is increased, r_i is increased correspondingly or $H_i^{\max}$ is decreased. Inversely, if this product is decreased, r_i is decreased correspondingly or $H_i^{\max}$ is increased. As a result, the amount $\left[p_i E_i \Delta d_i^{el}(f_i) H_i^{\max}\right]$ is balanced to hold the distortion fluctuation small for smooth playback.

4.2 Replication Implementation

The proposed optimal replication strategy is composed of three phases including pre-replication phase, implementation phase, and post-replication phase which are described in detail in the sequel.

4.2.1 Pre-replication Phase

In pre-replication phase, an arbitrary gateway first traces the inter- and intra-popularities of every video streaming which has been flowing into the backbone of WMNs from the Internet. If a video streaming becomes most popular enough, some essential parameters of the video such as video size, source distortion model, and the latest inter- and intra-popularities are extracted for replication process. Next, the gateway computes an amount of bit budget corresponding to a suitable encoding rate based on the average storage capacity of mesh routers, the average receive bandwidth of heterogeneous users, and the video size, so as to use the network resources efficiently. Then, the per-hop loss probability of each frame is estimated based on the latest per-hop expected bit error rate (BER) conveyed by an overlay network topology periodically [24]. Finally, according to the above considered parameters, a computation will be executed to find out optimal replication density for each frame so that the AMRD is minimized.

4.2.2 Implementation Phase

Following the optimal replication density for each frame, the video frames are replicated in some indicated mesh routers by the gateway. In this phase, Mod&Timer algorithm [25] is executed in every mesh router in order to handle the placement of replicas so that unnecessary replicas are reduced to prevent from the waste of storage capacity of network. It is important to note that during generating optimal replication density, there may have some frames with the same replication density. These frames will be grouped and replicated in the same mesh routers.

4.2.3 Post-replication Phase

After replicating, some essential services are deployed in order to maintain and update the replicas due to the random on/off of mesh routers and the change of users' behavior or/and network condition, respectively. Finally, all the replicas are released when the video becomes obsolete.

5. Performance Evaluations

In this section, we simulate to demonstrate that our method (named minimum AMRD, MAD) outperforms other optimal replication strategies, for example: minimum access cost (MAC, $r_i \propto p_i^{2/3}$) [11], minimum query cost (MQC, $r_i \propto p_i^{1/2}$) [23], and standard proportional strategy (PRO, $r_i \propto p_i$) which is often used as the reference strategy for comparison.

5.1 Simulation Setup

We deploy a grid topology of WMNs as in [6] and [12] with $N = 1000$ stationary mesh routers, and BER is uniformly distributed from 10^{-8} to 10^{-6}. For simplicity, we ignore the constant Ω by setting it to 1. Besides, we use the MPEG-4 Reference Software Version 2.5 [22] supported by Microsoft to analyze the Mobile sequence in CIF (352x288) resolution, 30fps. Due to the users' devices, e.g., PCs, Laptop, PDAs, etc., with limited and heterogeneous receive bandwidths, we should not encode the video in highest quality with full encoding rate (sometimes transmission rate) in order to save the bandwidth of network. In this paper, we assume that the Mobile sequence frequently required by the users, whose receive bandwidth equals 80% of the full encoding rate of the video. So, the size and the encoding PSNR of Mobile sequence are respectively equivalent to 20.89MBytes and 49.77dB, which represents a very high quality before replicating. All algorithms are implemented with 100 iterates for average result using Matlab.

5.2 Performance Metrics

5.2.1 Minimum AMRD for High PSNR

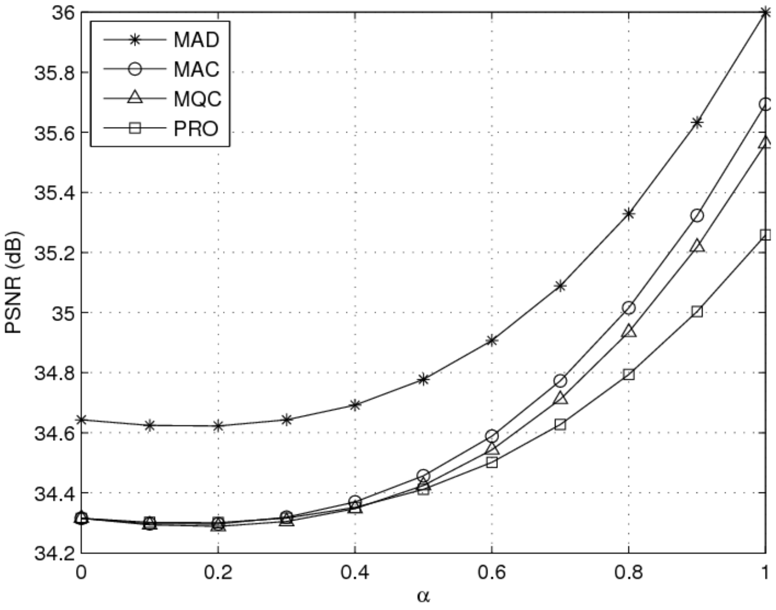

Fig. 2. PSNR performance versus user behavior, α.

Fig. 2 shows the AMRD performance represented by PSNR which is calculated based on the difference between the original sequence and the reconstructed sequence at the users. The PSNR is evaluated versus different user behavior conditions by changing the exponent of Zipf-like distribution, α. As illustrated in this figure, for all strategies, the performance is enhanced when α increases. This is because the skewed access probability of frame is more different and the AMTD is decreased as shown in **Fig. 3**. Thus, the frames suffer lower loss probability to be received at the users, resulting in higher PSNR of received Mobile sequence. Importantly, PSNR of our MAD outperforms the other three strategies, MAC, MQC, and PRO. The reason is that MAD exploits all the three skewed properties including access probability (p_i), loss probability (E_i), and encoding RD information ($\Delta d_i^{el}(f_i)$) of each frame to allocate correspondingly optimal replication density to each frame so that the ARMD is minimized for high PSNR. Meanwhile, MAC, MQC, and PRO cannot take full advantage of all these three skewed properties. Moreover, MAC and MQC show a better PSNR than PRO because it can not exploit the skewed access probability of each frame as the two formers.

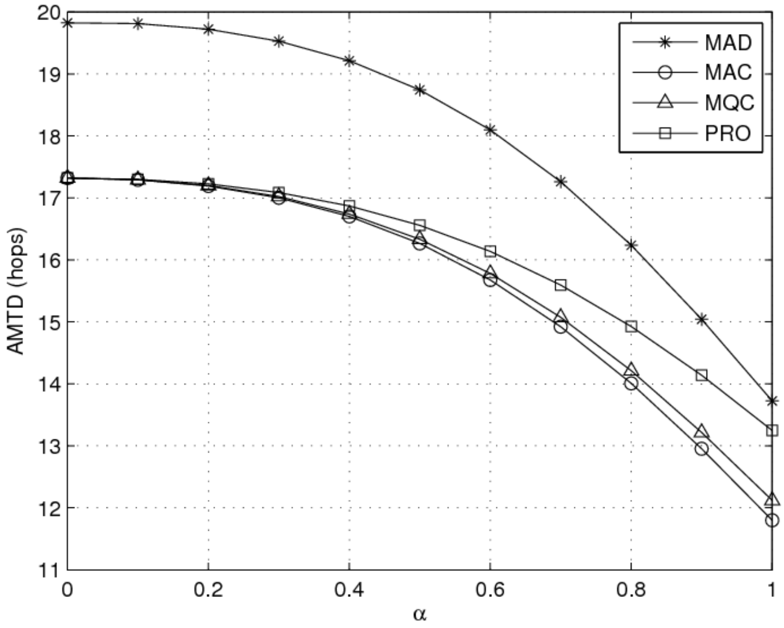

Fig. 3. Continuous playback performance versus user behavior, α.

5.2.2 Small Reconstructed Distortion Fluctuation for Smooth Playback

For smooth playback evaluation, we measure the PSNR fluctuation based on (6). As in **Fig. 4**, the simulation result shows that our method achieves the smallest fluctuation in terms of standard deviation of PSNR for smoothest playback. In particular, the minimum standard deviation of PSNR of MAC, MQC, and PRO is 3.60dB causing the Mobile sequence rough to be seen at the users, while it is significantly decreased to 2.44dB in MAD.

5.2.3 Reasonable AMTD for Continuous Playback

The tradeoff of our method is that we can not obtain the best performance in terms of minimum AMTD for continuous playback. As illustrated in **Fig. 3**, MAC is the best one with minimum AMTD. However, the AMTD of MAD, which is the worst case, is close to MAC and reaches more reasonable result for providing the users with continuous playback when α increases (i.e., more skewed intra popularity).

5.2.4 Small SCR for Saving the Resource of Network

As can be deduced from the minimum value of AMTD, the video frames in MAC are replicated with highest densities, leading to the result that MAC consumes the largest SCR for replicating compared to the other three strategies as shown in **Fig. 5**. And certainly, MAD outperforms MAC, MQC, and PRO in terms of saving the network resources with minimum SCR.

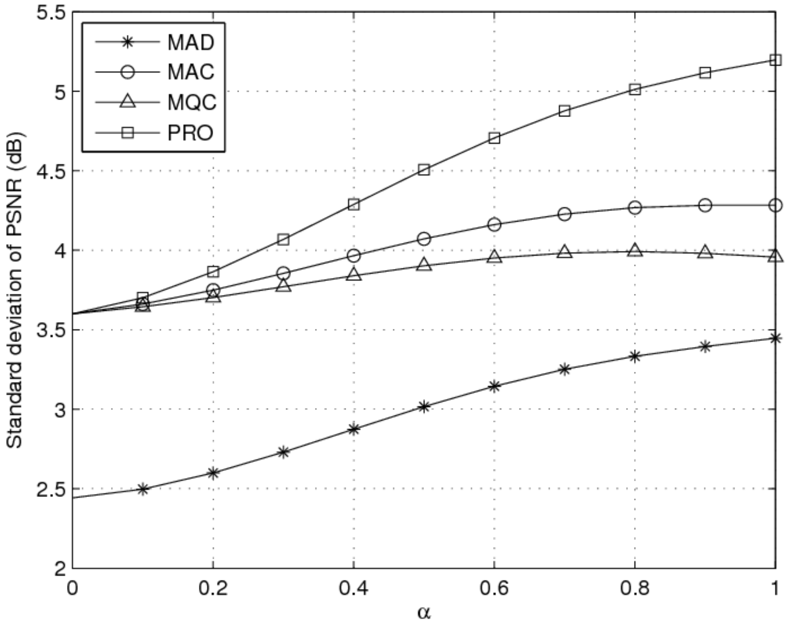

Fig. 4. Smooth playback performance versus user behavior, α.

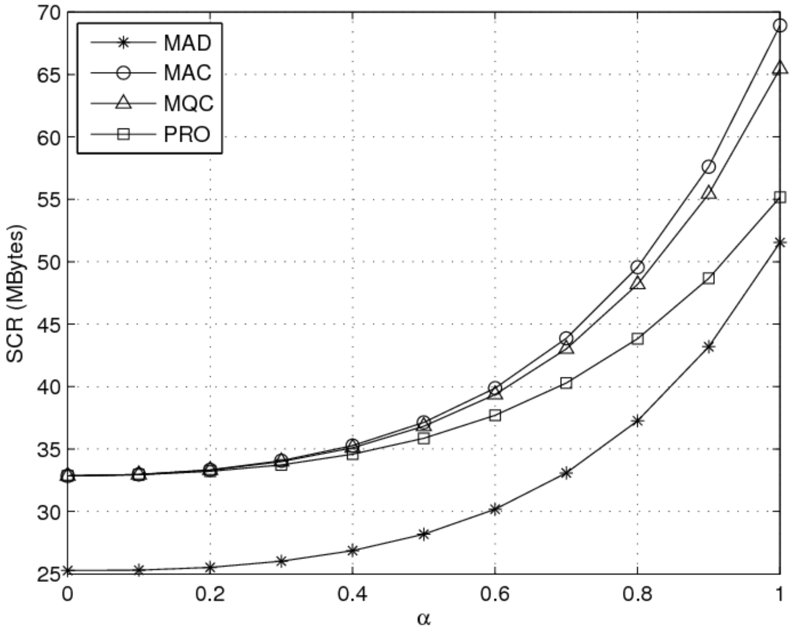

Fig. 5. SCR performance versus user behavior, α.

5.2.5 Summary of Performance Evaluation

Finally, for an overview of comparison, the performance evaluations of MAD, MAC, MQC, and PRO are briefly shown in **Table 1**.

Table 1. QoE and SCR comparisons

Metrics\Strategies	MAD	MAC	MQC	PRO
PSNR	Excellent	Good	Average	Poor
Smooth playback	Excellent	Average	Good	Poor
Continuous playback	Poor	Excellent	Good	Average
SCR saving	Excellent	Poor	Average	Good

5.3 Effect of Encoding Rate On Performance Metrics

In this subsection, we aim at proving that high encoding rate of video streaming does not always provide users with high UPQ in the presence of inherent problems of wireless environment (e.g., relatively unreliable connectivity, dynamically varying network topology, and limited resources), and meanwhile high SCR is consumed. To do so, we investigate the effect of encoding rate on the performance metrics of replication for video streaming by changing the rate from 10% to 100% of the full encoding rate of Mobile sequence.

As can be observed from **Fig. 6**, obviously, the PSNR of received video streaming is low if the video streaming is encoded at low rates, i.e, 10% to 20%, of the full encoding rate. However, we can see that the high rates, i.e., 80% to 100%, do not introduce high PSNR, even the PSNR becomes very low. In this case, the best range of rate is from 30% to 70% of the full encoding rate.

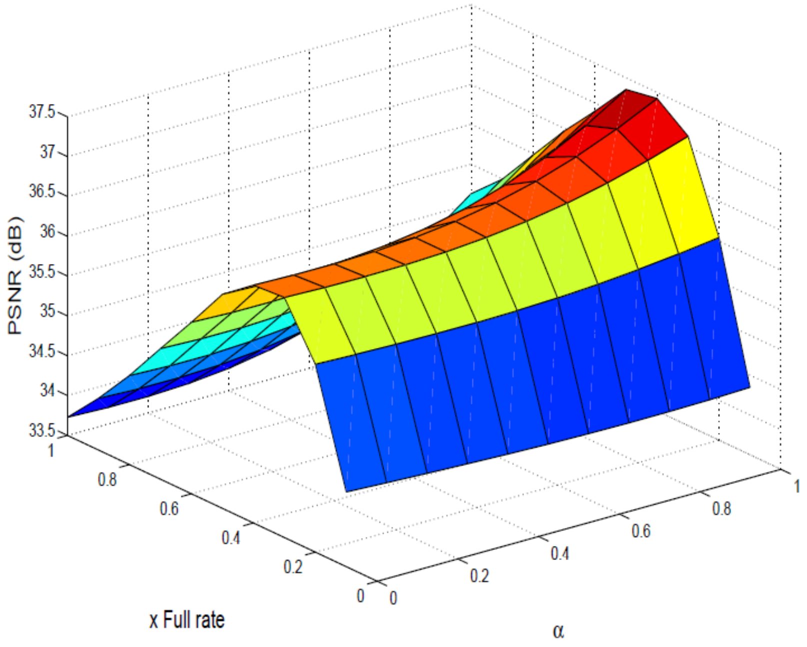

Fig. 6. The effect of rate on PSNR performance of MAD.

The **Fig. 7** obviously shows that the rate mostly has no effect on continuous playback performance. But, as illustrated in **Fig. 8** and **Fig. 9**, the rate deeply affects smooth playback and SCR performances. In **Fig. 8**, the higher rate at which the video is encoded, the higher quality/distortion fluctuation of received video streaming is perceived by the users. And clearly, in **Fig. 9**, the higher encoding rate requires more SCR for replicating.

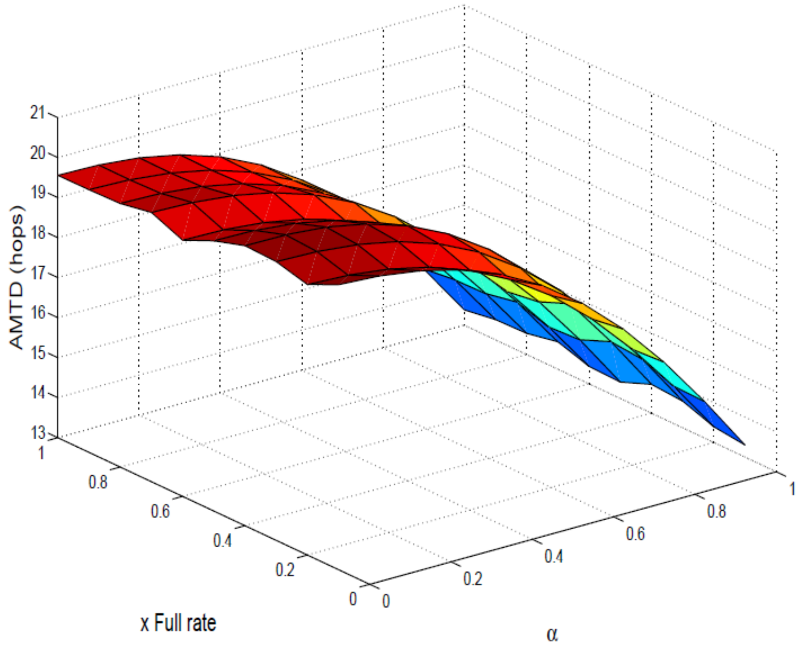

Fig. 7. The effect of rate on continuous playback performance of MAD.

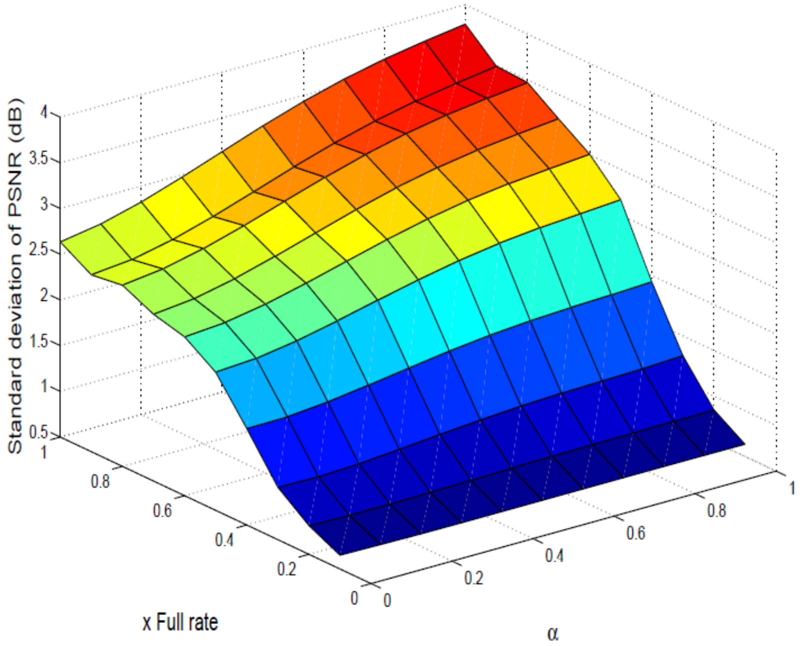

Fig. 8. The effect of rate on smooth playback performance of MAD.

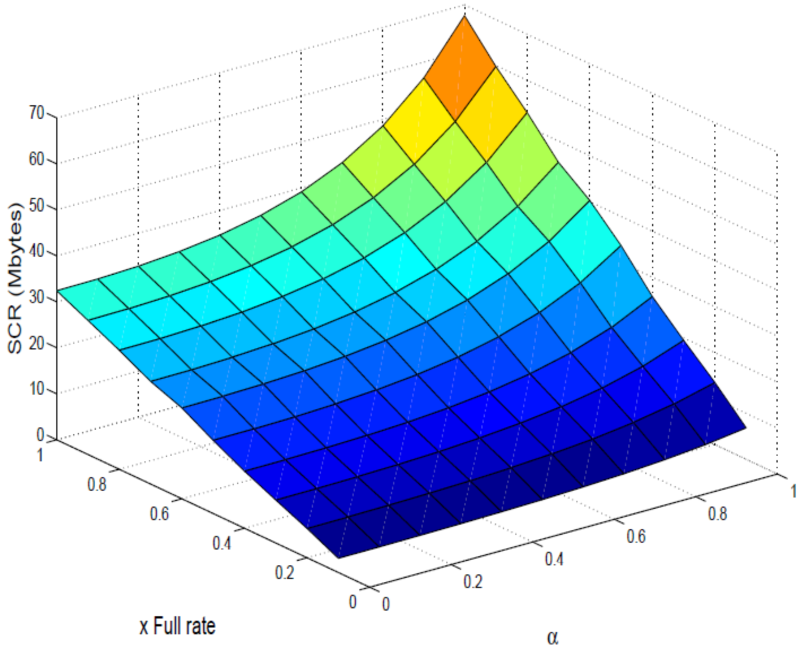

Fig. 9. The effect of rate on SCR performance of MAD.

6. Conclusions

We have proposed a novel replication strategy by finding the closed-form of optimal replication densities for a set of frames of a video based on exploiting the skewed values of each frame, i.e., access probability, loss probability, and encoding RD information. The simulation results have shown that our MAD improves the replication performance in terms of high UPQ including highest PSNR, smoothest playback, and reasonable continuous playback. In addition, the proposed method consumes the smallest SCR for replicating to save the resource of network. More importantly, we have investigated that high encoding rate does not necessarily imply high performance of replication for video streaming applications in WMNs.

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