Optimized Preference-Aware Multi-path Video Streaming with Scalable Video Coding

Anis Elgabli, Ke Liu, and Vaneet Aggarwal

Abstract—Most client hosts are equipped with multiple network interfaces (e.g., WiFi and cellular networks). Simultaneous access of multiple interfaces can significantly improve the users’ quality of experience (QoE) in video streaming. An intuitive approach to achieve it is to use Multi-path TCP (MPTCP). However, the deployment of MPTCP, especially with link preference, requires OS kernel update at both the client and server side, and a vast amount of commercial content providers do not support MPTCP. Thus, in this paper, we realize a multi-path video streaming algorithm in the application layer instead, by considering Scalable Video Coding (SVC), where each layer of every chunk can be fetched from only one of the orthogonal paths. We formulate the quality decisions of video chunks subject to the available bandwidth of the different paths and the chunk deadlines as an optimization problem. The objective is to jointly minimize the stall/skip duration of the video, maximize the average quality, and minimize the number of quality switches. Even though the formulation is a non-convex discrete optimization, we show that the problem can be solved optimally with a complexity that is quadratic in the video length. We further propose an online algorithm where several challenges including bandwidth prediction errors, are addressed. Finally, we give a set of novel preference-aware algorithms where one of the links is more expensive than the other. Extensive emulated experiments in a real testbed with real traces of public dataset reveal the robustness of our scheme and demonstrate its significant performance improvement compared to other multi-path algorithms.

Index Terms—Video Streaming, Multi-path, Scalable Video Coding, Video Quality, Stall Duration, Multi-path TCP, Discrete Optimization

I. INTRODUCTION

It is common that today’s client hosts are equipped with multiple network interfaces. For example, mobile devices (e.g., Apple iOS 7 [1]) inherently support WiFi and cellular networks at the same time. The provision of simultaneous access of the multiple interfaces significantly improves the performance of various applications, e.g., web browsing [2], as they can leverage the bandwidths of both the links (or paths). Video streaming is one of the major sources of traffic in mobile networks. While its popularity is on the rise, its quality of experiences (QoE) is still often far from satisfactory. In this paper, we propose a set of efficient video streaming algorithms to improve users’ QoE using multiple paths simultaneously.

An intuitive approach to enable multi-path is to replace the conventional transport (i.e., TCP) with Multi-path TCP (MPTCP [3]), which is the de-facto multi-path solution allowing applications to transparently use multiple paths. Specifically, MPTCP opens multiple sub-flows (usually one over each path), distributes the data onto the sub-flows at the sender, andreassembles data from each path at the receiver. The key advantage of MPTCP is that it allows applications to use multiple paths without changing the existing socket programming interface. Despite these advantages, the deployment of MPTCP is sluggish. A vast amount of commercial content providers do not support MPTCP [4], [5] because it requires OS kernel update at both the client and server side. To make things worse, MPTCP uses special TCP extensions that are often blocked by middle-boxes of the commercial content providers (e.g. MPTCP over Port 80/443 is blocked by most U.S. cellular carriers [6]). Implementing MPTCP with link preference further requires message exchange between the rate adaptation logic at the application layer and MPTCP in order to disable/enable parallel TCP connections. Thus, in this paper, we will consider an approach for fetching video encoded using scalable video coding (SVC) on multiple paths without the use of MPTCP.

There are two popular coding techniques, Advanced Video Coding (AVC, e.g. MPEG4-AVC) and Scalable Video Coding (SVC [7]). In AVC, each video chunk is stored into L independent encoding versions. When fetching a chunk, the player’s adaptation mechanism, Adaptive Bit Rate (ABR) streaming, needs to select one out of the L versions based on its estimation of the network condition and the buffer capacity.

In SVC, each chunk is encoded into ordered layers: one base layer (Layer 0) with the lowest playable quality, and multiple enhancement layers (Layer i > 0) that further improve the chunk quality based on layer i−1. For decoding a chunk up to enhancement layer i, a player must download all layers from 0 to i. Thus, adaptive SVC streaming can allow playback at a lower quality if all the enhancement layers have not been fetched while ABR streaming does not allow playback if the chunk is not fully downloaded. Adaptive SVC streaming has been shown to provide better adaptiveness and scalability than ABR [8], [9]. That is why we choose SVC as the coding scheme in this paper and propose a set of streaming algorithms using SVC.

Instead of using MPTCP, we realize “multi-path” in application layer, i.e., initiating a separate connection in the application (e.g., browser, video player) via one of the network interfaces/link (e.g., WiFi and LTE) using conventional TCP, and each layer of a chunk is fetched using one of the connections. Thus, the streaming algorithm decides whether to fetch a layer of the chunk or not, and which link to use for fetching. This approach requires no change to the server side and is compatible with any middle-box. We note that the different layers of a chunk can be fetched using different links using...
adaptive SVC streaming, while the entire chunk is fetched from the same link when using ABR. This flexibility helps to provide additional improvement on QoE compared to ABR-based mechanisms. As shown in Section VII our SVC-based multi-path streaming algorithms outperform one of the recent state-of-the-art ABR-based multi-path streaming algorithms, MSPlayer [4].

We consider two classes of streaming algorithms: skip based and no-skip based streaming. The former is for real-time streaming: each chunk is associated with a deadline, chunks not received by their deadlines are skipped. For no-skip based streaming, if a chunk cannot be received by its deadline, it will not be skipped; instead, a stall (re-buffering) will incur until it is fully received. For both the scenarios, we formulate the adaptive streaming algorithm as an optimization problem for perfectly predicted bandwidths of the two links, that maximizes the video quality and minimize the stalls/skips simultaneously (c.f., Section 3). Even though the formulation is a non-convex optimization problem, we can show that the optimal solution can be achieved by a polynomial-time (quadratic in video-length) algorithm. In practice, the future bandwidth cannot be perfectly predicted, but can be estimated for a smaller window ahead using a crowd-sourced method to obtain historical data [10], [11], or harmonic mean of the past bandwidth [4]. The perfect prediction case forms an upper bound to the algorithm performance with imperfect prediction. Our proposed adaptive streaming algorithms incorporate this imperfect information by using the bandwidth prediction methods in [10], [11], [4] (these prediction methods are not perfect thus have errors) as shown in the online algorithms in Section 3 and 4.

We also introduce a special case of our approach, i.e., a single path adaptive streaming algorithm that only one TCP connection is initiated and every video packet traversal is governed by MPTCP, which combines the WiFi and LTE links as a single link that has the total bandwidth of both links. This algorithm can be shown to be optimal and can be implemented by both adaptive SVC and ABR schemes.

In multi-path video streaming, one of the links is in general preferable as compared to the other. For instance, the users may not wish to use too much of cellular link since it is, in many cases, more expensive (limited plans) and less energy efficient (far from the base station). Therefore, we extend the proposed algorithms to the scenario where one of the links is used only if needed to help fetching chunks up to a higher layer. Both the skip based and no-skip based streaming classes are considered.

Our Contributions: The main contributions of the paper are as follows.

- We formulate the multi-path SVC video streaming with perfect bandwidth prediction as an optimization problem, whose objective is to maximize the users’ quality of experience (QoE). We consider two classes of streaming algorithms: skip based and no-skip based streaming. For both algorithms, the goal of the scheduling algorithm is to determine up to which layer we need to fetch for each chunk (except for those skipped in realtime streaming), such that the overall playback bitrate is maximized and the number of stalls or skipped chunks is minimized. We also propose an online algorithm for the scenario where bandwidth prediction is not perfect, i.e., available for short period ahead and has errors.
- The proposed problem is a non-convex discrete optimization problem, which is NP-hard in general since there are discrete variables and non-convex constraints. However, we develop an efficient algorithm that solves this specific problem optimally in polynomial time. Thus, we provide a class of discrete optimization problem that is solvable optimally in polynomial time under certain assumptions. Specifically, we solve the proposed integer-constrained problem using an easy-to-solve bin-packing based algorithm whose complexity is quadratic in the number of chunks.
- We propose streaming algorithms for the case in which one of the links is preferred over the other one. Both classes of streaming algorithms: skip based and no-skip based streaming are considered.
- We also propose special cases of our approach, i.e., a set of single path adaptive streaming algorithms using MPTCP for all the above cases, i.e., with and without preference, and skip-based or no-skip-based. These algorithms can be used on either of ABR or adaptive SVC schemes.
- We evaluated our algorithms using a TCP/IP test bed with real SVC encoded videos and bandwidth traces from public datasets collected from commercial networks. The evaluation demonstrates that our approach is robust to prediction errors, and works well with a short prediction window, where we estimate the bandwidth using harmonic mean of the bandwidth values of the past few seconds. Even though our formulation considers constant bit rate (CBR) encoding rate per layer, we evaluated our formulation and algorithms using Variable Bit Rate (VBR) encoded videos against a number of adaptive streaming strategies including the multi-path version of the buffer-based approach (MP-BBA) [12] and the prediction based algorithms such as MSPlayer [4]. The results demonstrate that our algorithm outperforms them by improving the key QoE metrics such as the playback quality, the number of layer switches, and the number of skips or stalls. For example, our skip based streaming algorithm was able to achieve average playback quality that is 25%, and 35% higher than MP-BBA and MSPlayer respectively with lower stall/skip durations. The preference-aware adaptive streaming algorithms were compared with the preference-aware MPTCP based algorithms in [13] and it is shown that the proposed algorithm obtains lower skips, higher average quality, and lower link 1 usage thus demonstrating improvement in all these metrics.

The rest of the paper is organized as follows. Section II discusses the related work. Section III describes the problem formulation for multi-path streaming without preference to any link. Further, a quadratic-time algorithm is provided for this non convex problem, and is shown to be optimal. The algorithm is extended to the case with the use of MPTCP, and online scenarios. Both skip and no-skip scenarios are considered. Section IV further considers preference of one link over the other, modeling the scenario where the users wish to use less cellular content. Section V presents the trace-
driven evaluation results with comparison to the different baselines. Sections [A] and [B] show the optimality of the proposed algorithms for the skip-based and no-skip based streaming, respectively, when there is no link preference. Section [VI] concludes the paper. The optimality for the preference based streaming is considered in the Appendix.

II. RELATED WORK

Video streaming has received a lot of attention from both the academia and industry in the past decade. There are ABR and adaptive SVC adaptation algorithms. Some of the widely used ABR streaming techniques include MPEG-DASH [14], Apple’s HLS [15], Microsoft’s Smooth Streaming [16], and Adobe’s HDS [17]. In recent studies, various approaches for making ABR streaming decisions have been investigated, for example, by using control theory [18], [19], Markov Decision Process [20], machine learning [21], client buffer information [12], and data-driven techniques [22], [23], [24].

SVC received the final approval to be standardized as an amendment of the H.264/MPEG-4 AVC (Advanced Video Coding) standard in 2007 [25]. Although much less academic research has been conducted on SVC compared to AVC-style schemes over regular H.264, there exist some studies of using SVC to adapt video playback quality to network conditions. A prior study [26] proposed a server-based quality adaptation mechanism that performs coarse-grained rate adaptation by adding or dropping layers of a video stream. While this mechanism was designed to be used over UDP with a TCP-friendly rate control, more recent research has explored techniques that use SVC over HTTP. A study [9] compared SVC with regular H.264 encoding (H.264/AVC). Their results suggest SVC outperforms AVC for scenarios such as VoD and IPTV through more effective rate adaptation. The work [27] published the first dataset and toolchain for SVC. Some prior work [28], [29] proposed new rate adaptation algorithms for SVC that prefetch future base layers and backfill current enhancement layers. Even though optimization-based formulations have been proposed for video streaming in the past [13], [30], [31], [32], the optimality guarantees for the proposed algorithms are limited. In contrast, this paper shows the optimality of the proposed algorithm for a non-convex discrete optimization problem.

The knowledge of the future network conditions can play an important role in Internet video streaming. A prior study [33] investigated the performance gap between state-of-the-art streaming approaches and the approach with accurate bandwidth prediction. The results indicate that prediction brings additional performance boost for ABR streaming, and thus motivates our study. The bandwidth have been shown to be predictable for some time ahead using a crowd-sourced method to obtain historical data [10], [11], or harmonic mean of the past bandwidth [4].

Adaptive streaming strategies have been proposed for multi-path channels in [4] where a heuristic based on prediction, MSPlayer, was proposed for streaming AVC video using WiFi and LTE. In their proposed heuristic, alternate chunks are downloaded using WiFi and LTE connections respectively. The key differences with this work are: 1) We use the flexibility of SVC, where the different layers can be fetched over different paths, and 2) The proposed algorithm is shown to be optimal for the considered formulation. Recently, the authors of [13] gave novel algorithms for using multi-path TCP to stream AVC videos where the primary objective was to reduce the usage of LTE as well as minimizing the stall. The approach in [13] uses a rate adaptation algorithm, like BBA [12] or Festive [23], and uses MPTCP to fetch AVC videos at the same quality levels while reducing the usage of LTE. This approach works on top of rate adaptation techniques, which do not explicitly minimize LTE usage in their objective. In contrast, this paper propose algorithms that consider preference of one link over the other explicitly and use the approach of [13] as a comparison. Moreover, [13] considered use of MPTCP and a no-skip based version. However, in this paper we consider both skip and no-skip based scenarios, as well as both options of using or not using MPTCP. The versions that use MPTCP in this paper can also be used directly using AVC rather than SVC since they do not exploit fetching a layer from only one of the links.

III. MULTI-PATH VIDEO STREAMING WITHOUT PREFERENCE

In this section, we will describe the algorithms for adaptively streaming SVC videos over multi-path. We will consider two links (e.g., WiFi and cellular networks) in the exposition, but the formulation and proposed algorithms can be easily extended to more links. We consider two scenarios: the skip based streaming and the no-skip based streaming. For the skip based streaming, the video is played with an initial start-up, (i.e., buffering) delay $s$ and there is a playback deadline for each of the chunks where chunk $i$ need to be downloaded by time $\text{deadline}(i)$. Chunks not received by their respective deadlines are skipped. For the no-skip based streaming, it also has a start-up delay. However, if a chunk cannot be downloaded by its deadline, it will not be skipped. Instead, a stall (i.e., re-buffering) will occur, i.e., the video will pause until the chunk is fully downloaded. In both scenarios, the goal of the scheduling algorithm is to determine up to which layer we need to fetch for each chunk (except for those skipped), such that the number of stalls or skipped chunks is minimized as the first priority and the overall playback bitrate is maximized as the next priority. Further, we need to determine which of the two paths to use to fetch each layer of each chunk that is decided to be downloaded.

A. Skip Based Streaming: Offline Problem Formulation

We first assume that the future bandwidth is perfectly known beforehand, the buffer capacity is infinite, and each layer is encoded at constant bit rate (CBR). In other words, all chunks have the same $n$th layer size. We will relax both the perfect prediction and the infinite buffer size assumptions later on in this section. Moreover, we will evaluate the proposed algorithm with videos that are encoded at Variable Bit Rates (VBR). With these assumptions, we give a formulation for skip based video streaming. Let us assume a video divided
into $C$ chunks (segments), where every chunk is of length $L$ seconds, is encoded in Base Layer (BL) with rate $r_0$ and $N$ enhancement layers ($E_1, \cdots, E_N$) with rates $r_1, \cdots, r_N$, respectively. Note that $Y_n = L + r_n$ is the size of the $n$th layer. $Z_{n,i}$ denotes the size of the $n$th layer that has been fetched. Therefore, if the $n$th layer can be fetched $Z_{n,i} = Y_n$; otherwise $Z_{n,i} = 0$.

Let $z_{1}(i,j)$ be the size of layer $n$ of chunk $i$ fetched over the first link (e.g., LTE link) at time slot $j$, and $z_{2}(i,j)$ be the size of the layer $n$ of chunk $i$ over the second link (e.g., WiFi link) at time slot $j$. Let $B^{(k)}(j)$ be the available bandwidth over the link $k \in \{1, 2\}$ at time $j$ and $s$ be the startup delay. As mentioned, for the time being we assume the bandwidth can be perfectly predicted and we will relax this assumption in Section III-B. We assume all time units are discrete and the discretization time unit is assumed to be 1 second.

We start by assuming that the decision is taken at the application layer where a layer of a chunk cannot be split over the two paths (or links). It must be fully downloaded over either of the paths. In other words, $(\sum_{j=1}^{(i-1)L+s} z_{1}(i,j)) (\sum_{j=1}^{(i-1)L+s} z_{2}(i,j)) = 0$ for all $n$ and $i$. Their key objectives of the problem are (i) minimization of the number of skipped chunks, (ii) maximization of the average playback rate of the video, and (iii) minimization of the quality changes between the neighboring chunks to ensure that perceived quality is smooth.

In order to account for the first two objectives, we consider an optimization objective of $\sum_{n=0}^{N-2} \gamma^n \sum_{i=1}^{C} Z_{n,i}$. We assume $0 < \gamma < 1$ small, and more precisely

$$C \sum_{j=1}^{N-2} \gamma^j r_{a+j} < r_a,$$  \quad \text{for } a = 0, \cdots, N. \quad (1)$$

This choice of $\gamma$ implies that all the higher layers than layer $a$ have lower utility than a chunk at layer $a$ for all $a$. For $a = 0$, this implies that all the enhancement layers have less utility than a chunk at the base layer. Thus, the avoidance of skips is the highest priority. The use of $\gamma$ helps in giving higher priority to fetch more chunks up to $n$th layer quality over fetching some at higher quality in the cost of fetching other chunks at quality that is below $n$th layer. In other words, it prioritizes horizontal over vertical scan, and implicitly, this will also reduce unnecessary layer switching. Note that the user gets a strictly increasing utility depending on the rate it watches the video. The utility function is most often considered to be a concave function. Thus, the rate of increase in the utility decreases with the play-back rate and hence the weights of lower layers are much higher than those of higher layers. Overall, the multi-path SVC layer scheduling problem with the knowledge of future bandwidth information can be formulated as follows.

$$\text{maximize } \sum_{n=0}^{N} \gamma^n \sum_{i=1}^{C} Z_{n,i} \quad (2)$$

subject to

$$\sum_{j=1}^{(i-1)L+s} z_{1}^{(2)}(i,j) + z_{1}^{(1)}(i,j) = Z_{n,i} \quad \forall i, n \quad (3)$$

$$Z_{n,i} = \frac{Y_n}{Y_{n-1}} Z_{n-1,i} \quad \forall i, n > 0 \quad (4)$$

$$\sum_{n=0}^{C} \sum_{i=1}^{C} z_{2}(i,j) \leq B^{(k)}(j) \quad \forall k \in \{1, 2\}, \forall j, \quad (5)$$

$$\left(\sum_{j=1}^{(i-1)L+s} z_{1}^{(1)}(i,j)\right) \left(\sum_{j=1}^{(i-1)L+s} z_{2}^{(2)}(i,j)\right) = 0 \quad \forall i, n \quad (6)$$

$$z_{2}(i,j) \geq 0 \quad \forall k \in \{1, 2\}, \forall i \quad (7)$$

$$z_{2}(i,j) = 0 \quad \forall i : (i - 1)L + s > j, k \in \{1, 2\} \quad (8)$$

$$Z_{n,i} \in Z_n \triangleq \{0, Y_n\} \quad \forall i, n \quad (9)$$

Variables: $z_{2}(i,j), z_{1}^{(1)}(i,j), Z_{n,i} \quad \forall i = 1, \cdots, C, \quad j = 1, \cdots, (C-1)L + s, n = 0, \cdots, N$

In the above formulation, we have $0 < \gamma < 1$ constrained by (1). so we prioritize lower layers compared to higher layers as mentioned earlier. Constraints (3) and (9) ensure that what is fetched for layer $n$ of chunk $i$ over all links and times to be either zero or $Y_n$. The constraint (4) ensures that $n$th layer of any chunk cannot be fetched if the lower layer has not been fetched. (5) imposes the bandwidth constraint of the two links at each time slot $j$. Constraint (6) enforces a layer of a chunk to be fetched only over one of the paths. Constraint (7) imposes the non-negativity of the download of a chunk and (8) imposes the deadline constraint since chunk $i \in \{1, \cdots, C\}$ cannot be fetched after its deadline (deadline(i) = (i - 1)L + s). Recall that $s$ is the initial startup delay.

B. Structure of the Proposed Problem

The problem defined in III-A has integer constraints and a non-convex constraint (in (9)). Integer-constrained problems are in the class of discrete optimization. Some of the problems in this class are the Knapsack problem, Cutting stock problem, Bin packing problem, and Traveling salesman problem. These problems are all known to be NP hard. Very limited problems in this class of discrete optimization are known to be solvable in polynomial time, some typical examples being shortest path trees, flows and circulations, spanning trees, matching, and matroid problems. The well-known Knapsack problem optimizes a linear function with a single linear constraint (for integer variables), and is known to be NP hard. The optimization problem defined in this paper has multiple constraints (including non-convex constraints), and does not lie in any class of known problems that are polynomially-time solvable to the best of our knowledge.
We note that optimization based formulations have been proposed earlier for video streaming \[\textnormal{[18], [30], [31], [32].}\] However, the optimality of these algorithms have not been considered due to integer constraints. The non-convex constraint in \(\textnormal{[3]}\) further increases the problem complexity beyond the proposed ILP formulations in \[\textnormal{[30], [31].}\] In this paper, we will show that the proposed optimization problem can be solved optimally in polynomial time. However, the result is not for general parameters and hold when \(\textnormal{[1]}\) is satisfied. As explained earlier, this range is meaningful to reduce the skips, and preference of lower layers to higher layers.

C. Efficient Quadratic-time Solution

In this section, we describe our proposed algorithm “Multi-Path SVC Algorithm” (MP-SVC), which is summarized in Algorithm \[\textnormal{[4]}\]. This algorithm first makes the decisions for the base layer (i.e., which chunks to be skipped, and which to be fetched over link \(k, k \in \{1, 2\}\)). The algorithm performs backward scan starting from the deadline of the last chunk (line 7) and checks the possibility of fetching chunks according to the available bandwidth (line 10, where \(r^{(k)}(j)\) is the cumulative available bandwidth of the link \(k\) up to the \(j\)th time slot). Given the decisions of chunks \(i + 1, \ldots, L\), we wish to decide which of the two links should chunk \(i\) be fetched at, such that the objective function is maximized while satisfying the constraints. For both choices of links at which chunk \(i\) can be fetched, we compute the residual total bandwidth (sum of the bandwidths of the two links) that will remain for the download of chunks \(1, \ldots, i - 1\). The link choice that maximizes the residual total bandwidth is chosen to fetch chunk \(i\) (Algorithm 2).

Note that the algorithm is similar to dynamic programming, where the algorithm decides the quality at which the chunks will be fetched starting from the last one. The link over which the chunk \(i\) is fetched is the one that gives the maximum amount of total available bandwidth over the two links before the deadline of chunk numbered \(i - 1\). For example, consider that fetching the \(i\)-th chunk over the link 1 results in using \(x\) amount of the bandwidth before the deadline of \(i - 1\)-th chunk while fetching the \(i\)th chunk over link 2 results in using \(y\) amount of the bandwidth before the deadline of \(i - 1\)th chunk. Then, the first link will be chosen to fetch the chunk \(i\) if \(x < y\).

Once the base layer decision is taken, the algorithm sequentially decides to fetch the enhancement layers.

Enhancement layer modifications: The algorithm proceeds in a similar fashion to decide for the next higher layer and so on. The bandwidth is now modified to be the remaining bandwidth after excluding whatever used to fetch lower layers (line 10, Algorithm 2). Also note that \(nf\)th layer for a chunk is not fetched if its \((nf - 1)\)th layer was not fetched (line 9, Algorithm 2).

Complexity Analysis: The algorithm sequentially decides each layer one after the other, and thus it is enough to find the complexity of one layer to compute overall algorithm complexity. For each layer \(n\), the algorithm first finds the cumulative bandwidth of every time slot \(j\), \(r^{(k)}(j)\) which is linear complexity. Then, it starts from the last chunk, and

**Algorithm 1** Offline-MP-SVC Algorithm

1. **Input:** \(Y = \{Y_i, \forall i\}, L, s, C, B^{(k)} = \{B^{(k)}(j), \forall j\}, k = 1, 2,\)
2. **Output:** \(I^{(k)}(t), k = 1, 2, 3\) set containing the indices of the chunks that can have their \(n\)th layer fetched over link \(k\).
3. **deadline** \((i) = (i - 1)L + s \\forall i\)
4. \(r^{(k)}(j) = \sum_{j = 1}^{j - 1} B^{(k)}(j), j = 1, \ldots, \text{\texttt{deadline}}(C), k = 1, 2\)
5. for each layer \(n = 0, \ldots, N\) do
   - \(j_1 = j_2 = \text{\texttt{deadline}}(C)\)
   - for \(i = C : -1 : 1\) do
     - \(j_k = \min(j_k, \text{\texttt{deadline}}(i)), k = 1, 2\)
     - if \(\max(r^{(1)}(j_1), r^{(2)}(j_2)) \geq Y_n\) then
       - \(I^{(k)}(t), B^{(k)}(j), Y_n) = \text{\texttt{Backward}}(i, j_k, \{r^{(k)}(j)\})\) \(\forall k, j \in \{1, 2\}\) do
       - \(\text{tmp}(k) = (1 - n f^{(k)}(r^{(k)}(I^{(k)}(t)))) + r^{(k)}(\text{\texttt{deadline}}(i - 1)), k = 1, 2\)
       - \(k_1 = \max(\text{tmp}(k))\)
       - if \((r^{(k_1)}(\text{\texttt{deadline}}(i)) \geq Y_n)\) then
         - \(I^{(k_1)} = I^{(k_1)} \cup i\)
         - \(B^{(k_1)} = B^{(k_1)} \cup j\)
         - \(r^{(k_1)} = R^{(k_1)}\)
       - end if
     - end if
   - end for
   - end for
   - end if
   - end for

**Algorithm 2** Backward Algorithm

1. **Input:** \(i, j, r, B, Y\)
2. **Output:** \(R \) is the residual cumulative bandwidth at different times after fetching chunk \(i\), \(B2\) is the residual bandwidth after accounting for fetching of chunk \(i\), \(j2\) is the index at which chunk \(i\) starts being fetched, \(nf\) determines whether chunk \(i\) can be fetched, 1 if it can’t be fetched
3. **Initialization:**
4. \(i = C, nf = 0\)
5. if \(r < Y_n\) then
6. \(nf = 1\)
7. else
8. while \((Y_n > 0)\) do
9. \(\text{\texttt{fetched}} = \min(B(j), Y_n)\)
10. \(B(j) = B(j) - \text{\texttt{fetched}}, r(j) = r(j) - \text{\texttt{fetched}}, Y_n(i) = Y_n(i) - \text{\texttt{fetched}}\)
11. if \((B(j) = 0)\) then \(j = j - 1\)
12. \(R = r, B2 = B, j2 = j\)
13. end while
14. end if

performs the backward algorithm on each link at each time. The backward algorithm determines whether the chunk can be fetched in that link and the amount of residual bandwidth. Since the complexity of backward algorithm is linear in \(C\), the overall complexity for a layer is \(O(C^2)\). Thus, the overall complexity is \(O(\sqrt{NC^2})\).

**Remark 1.** In our algorithm, with the use of \(\gamma\), the lower layers have higher priority than the higher layers. The algorithm also prefers to utilize the excess bandwidth to fetch the later chunks rather than earlier chunks. Hence, our proposed algorithm reduces the un-necessary quality variation across neighboring chunks.

**Remark 2.** We note that if one can use Multi-path TCP, the above algorithm can be used on only one path by assigning the sum of the bandwidths of the two links to this path and
having the bandwidth of the other path as zero. The streaming algorithm that utilizes Multi-path TCP is denoted as MPTCP-SVC. Further, this algorithm can be used for both AVC and SVC encoding since the decisions of the quality can be used with any of the encoding methods.

Remark 3. MPTCP-SVC will perform no worse than MP-SVC, since utilizing multipath TCP, each chunk will finish downloading no later than using MP-SVC. Thus, there will be a loss in performance as compared to the use of multipath TCP.

Remark 4. The algorithm can be easily extended to the case when there are more than 2 links where each layer of a chunk is assigned to the link that leaves more total residual bandwidth to the earlier chunks.

D. Optimality of the MP-SVC

In this section, we prove that the proposed algorithm achieves the optimal solution of problem (10). The detailed proofs are provided in Section A. The following result shows that the proposed algorithm minimizes the number of skips for a given layer among all the other algorithms which fetches the same quality levels up to the immediate next lower layer.

Lemma 1. Given size decisions up to (n - 1)th layer (Z0,...,Zn-1), remaining bandwidth, and deadline(i) for every chunk i, the proposed algorithm achieves the minimum number of nth layer skips (or obtains the maximum number of chunks at layer n) as compared to any feasible algorithm which fetches the same layers of every chunk up to layer n - 1.

Intuitively, the proposed algorithm pushes all the skips as early as possible since the earlier chunks will be closer to their deadlines, so skipping those will offer more bandwidth to the later ones, minimize the number of current layer skips, and maximize the number of candidate chunks to the next layer. The next result demonstrates that the proposed algorithm leaves the maximum possible bandwidth before the deadline of every chunk that is a candidate (has all previous layers fetched) to the next layer.

Lemma 2. Among all algorithms with the same number of nth layer skips, the proposed algorithm leaves the largest possible bandwidth for fetching the (n + 1)th layer of every candidate chunk before its deadline. In other words, the proposed algorithm maximizes the resources to the higher layer among all algorithms that have same decisions up to the current layer.

Intuitively, our proposed algorithm optimizes the bandwidth resources to make more resources available for later layers. This is essential for optimality of the algorithm since the decisions for the higher layers depend on the decisions of the lower layers. Thus, if the decision of the lower layer does not help giving more resources for the higher layers, the algorithm will not be optimal. Using Lemma 1 and Lemma 2, the following result shows the optimality of MP-SVC algorithm in solving problem (10).

Theorem 1. Up to a given enhancement layer M, M ≥ 0, if Zm,i is the size of every layer m ≤ M of chunk i that is found by running MP-SVC algorithm, and Zm,i′ is a size that is found by any other feasible algorithm such that all constraints are satisfied, then the following holds when γ satisfies (1).

\[
\sum_{m=0}^{M} \gamma^m \sum_{i=1}^{C} Z_{m,i} \leq \sum_{m=0}^{M} \gamma^m \sum_{i=1}^{C} Z_{m,i}^*.
\]

In other words, MP-SVC finds the optimal solution to the optimization problem (10) when γ satisfies (1).

Intuitively, note that MP-SVC first fetches the lower quality level of all the chunks before fetching the next higher levels. Thus, the QoE attained is higher. It also prefers the excess bandwidth to be utilized for fetching higher quality layers of the later chunks. Finally, since MP-SVC minimizes the skips, thus, it is the optimal.

E. Online Algorithm: Dealing with Unavailable and Inaccurate BW Prediction

For the algorithm described in Section III-C we assumed that perfect bandwidth prediction, and client buffer capacity is unlimited. However, practically, the prediction will not be perfect, and the client buffer might be limited. In this section, we will use an online algorithm that will obtain prediction for a window of size W chunks ahead and make decisions based on the prediction. Note that the buffer capacity at the user may be limited, and in that case we consider that W is no more than the buffer capacity since the chunks beyond that will not be fetched in the algorithm. The way we capture the buffer capacity is by assuming that at every re-run of the algorithm (every α seconds), only chunks that are Bmax ahead of the chunk that is currently being played can be fetched. There are multiple ways to obtain the prediction, including a crowdsourced method to obtain historical data [10], [11]. Another approach may be to use a function of the past data rates sourced method to obtain historical data [10], [11]. The decisions are re-computed for the chunks that have not yet reached their deadlines periodically every α seconds.

For the prediction window W, the algorithm in Section III-C is run to find the quality using the predicted bandwidth profile, then the W chunks are fetched according to the algorithm decision. For the prediction window W, the algorithm in Section III-C is run to find the quality using the predicted bandwidth profile, then the W chunks are fetched according to the algorithm decision. If all W chunks are fetched before the next re-computation time, the current time is set as the re-computation point, and the fetching policy for the next W chunks from the one that is currently being played is computed. If the buffer occupancy is lower than a pre-decided threshold Bmin, chunks are fetched at most in base layer, which also includes the fetching of the first few chunks. Finally, at the start of the download, all links are assigned chunks at base layer quality to fetch since there is no bandwidth prediction available yet.
F. No Skip Based Streaming Algorithm

In no-skip streaming (i.e., watching a pre-recorded video), when the deadline of a chunk cannot be met, rather than skipping it, the player will stall the video and continue downloading the chunk. The objective here is to maximize the average quality while minimizing the stall duration (the re-buffering time). The objective function is slightly different from equation (2) since we do not allow to skip the base layer. However, we skip higher layers. For the constraints, all constraints are the same as skip based optimization problem except that we add constraint (16) to enforce the base layer (BL) size to be equal to the BL size of the chunk (it can’t be zero). We define the total stall (re-buffering) duration from the start till the play-time of chunk \( i \) as \( d(i) \). Therefore, the deadline of any chunk \( i \) is \( (i-1)L + s + d(i) \). The objective function is thus given as

\[
\max \left( \sum_{i=1}^{N} \gamma_{i} \sum_{j=1}^{C_{i}} Z_{n,i} - \mu \sum_{i=1}^{C_{i}} d(i) \right)
\]

subject to \([4], [5], [7], [9]\).

\[
(i-1)L+s+d(i)
\]

\[
\sum_{j=1}^{C_{i}} z_{n}^{(2)}(i, j) + z_{n}^{(1)}(i, j) = Z_{n,i} \quad \forall i, n
\]

\[
\left(\sum_{j=1}^{C_{i}} z_{n}^{(1)}(i, j) - \sum_{j=1}^{C_{i}} z_{n}^{(2)}(i, j)\right) = 0 \quad \forall i, n
\]

\[
z_{n}^{(k)}(i, j) = 0 \forall \{i : (i-1)L+s+d(i) > j\}, k \in \{1, 2\}
\]

\[
d(i) \geq d(i-1) \geq 0 \quad \forall i > 0
\]

\[
Z_{0,i} = Y_{0}
\]

Variables: \( z_{n}^{(2)}(i, j), z_{n}^{(1)}(i, j), Z_{n,i}, d(i) \forall i = 1, \cdots, C, j = 1, \cdots, (C - 1)L + s + d(C), n = 0, \cdots, N \)

We note that this problem can be solved using an algorithm similar to that for the skip-based streaming. One difference as compared to the skip version is that the first step of the no-skip algorithm is to determine the minimum stall time since that is the first priority. Therefore, The No-Skip MP-SVC algorithm initially runs initial forward scan with the objective of checking if all chunks can be fetched at least at base layer quality with the current startup delay. In high level, the forward algorithm simulates fetching the chunks in order starting from the first chunk and assigning each chunk to the link that fetches it the earliest. If a chunk \( i \) exceeds its deadline and it is not yet fully downloaded, initially, the deadline of all chunks \( i \) is shifted by the time duration needed to fully download the chunk. Then, the algorithm checks the time in which the last chunk was fully downloaded. If the time slot in which the last chunk (chunk C) is fetched was higher than its initial deadline \( (i-1)L+s \), the deadline of every chunk \( i \) will be: \( \text{deadline}(i) = (i-1)L+s+d(C) \) (Note this is final deadline and can’t be changed, but the chunk assignment is not final yet).

Note that increasing the start-up delay will not reduce the penalty term for the duration of stalls, hence, our algorithm will still give the minimum possible duration of stalls. We are only shifting the stalls to the beginning of the video in order to provide a smooth viewing experience and increase the opportunity of fetching higher layers of later chunks. This increased opportunity for fetching higher layers is indeed essential to prove the optimality of the proposed algorithm.

The rest of the algorithm is equivalent to skip version since skips are not allowed only for base layers (higher layers can be skipped). The detailed steps are given in Algorithm [3]. The key difference in the no-skip version is that the startup delay is decided such that there will be no skips. All the lemmas and optimality theorems of skip version are applicable to no-skip version, and the detailed optimality statements are given in Section [3].

**Online No Skip MP-SVC Algorithm**: In reality, we may not be able to predict the bandwidth for the entire video upfront, and thus all the stalls cannot be moved to the start. Based on the sliding window based approach described in Section [III-E] we bring the stalls in the window \( W \) to the start of the window. After this change, the rest of the algorithm does similar adaptations to the offline schedules as in Section [III-E].

IV. Multi-Path Video Streaming with Link Preference

In this section, we consider a preference to the use of link 2 as compared to link 1. We first assume that there is a parameter \( m \in \{0, \cdots, N\} \) indicating that the link 1 should not be used to obtain chunks above layer \( m \). This will allow using link 1
to help getting lower layers while not over-using it to achieve higher layers. Further, among different schemes that obtains same number of chunks till layer $m$, we wish to minimize the usage of link 1. For $m = 0$, this implies that link 1 is only used to avoid skips and not to fetch any enhancement layers. Further, link 1 is used only if necessary to reduce skips, when link 2 is not sufficient to obtain the optimal number of base layer chunks. The modifications to the no-skip version are similar to that discussed in Section III-F.

Accounting for the preference of link 2 over link 1, we propose an algorithm called “Multi-Path-Pref SVC Algorithm” (MP-Pref-SVC) which is summarized in Algorithm 4. In the first step, we use the MP-SVC algorithm for layers $n = 0$ to $m$. Then, we wish to minimize the use of Link 1 such that the decisions till layer $m$ remain the same. In order to do that, we use algorithm Link1-Save, summarized in Algorithm 5 which uses the decisions till layer $m$ and tries to find the new bandwidth of link 1, $B^{(1)}$, which is needed to get the same quality decisions. $R$ is initialized as zero. Link1-Save simulates fetching the layers based on the Step 1 decisions up to layer $m$. We proceed in order of chunks and for each chunk, we consider layers one after the other to see if it can be fetched with link 2. If a particular layer of a chunk cannot be fetched using link 2, then $R$ is incremented by the size of this layer. We keep continuing for all chunks and layers to get the final value of $R$. The output bandwidth profile $B^{(1)}$ is the same as input bandwidth profile $B^{(1)}$, except that it becomes zero after the cumulative sum reaches $R$ (lines 13-23, Algorithm 5). Thus, the cumulative sum of $B^{(1)}$ is $R$. We note that if all the same decisions can be obtained using link 2, link 1 is not used at all since $R = 0$. In short, if a layer of a chunk is not possible in order to be obtained using link 2, the corresponding bandwidth from link 1 is assigned to get that. Using these bandwidth decisions of link 1, we know that the chunks at the same quality up to $m$ can be obtained. Thus, as the last step, this bandwidth decision of link 1 is used as the bandwidth of link 1 and MP-SVC algorithm is run for all the layers. This gives the overall fetching solution of all the chunks. The key reason the bandwidth of link 1 is assigned from the start is to have maximum flexibility to help increase quality for higher layers. This algorithm can be shown to be optimal for $m = 0$ for a problem formulation described in Appendix C. These steps will also be extended to an online algorithm using the similar steps as in Section III-F.

We now consider an algorithm with Multi-path TCP. In this algorithm, we first run MPTCP-SVC algorithm for layers $n = 0$ to $m$. Then, the above algorithm is used to find $R$ with a difference that the partial amount of bandwidth that is missing to fetch using link 1 is added to $R$. Having computed the updated link 1 bandwidth, the third step is to run MPTCP-SVC on the single link with a bandwidth which point-wise adds the link 2 bandwidth and that of the link 1 obtained in the second step. As explained in Appendix C this variant that uses MPTCP will be optimal for the problem formulation described in Appendix C.

### Algorithm 4 Offline MP-Pref-SVC Algorithm

1: Run MP-SVC algorithm for layers $n = 0$ to $m$
2: $B^{(1)}_{\text{Link1-Save}}(C, B^{(k)}_{\text{Y}}, R^{(k)}_{\text{Y}}, k = 1, 2, n = 0, \ldots, m)$
3: Run MP-SVC algorithm for all layers. i.e $n = 0$ to $N$

### Algorithm 5 Link1-Save

1: Obtain $a_i$, which is the layer index till which chunk $i$ must be fetched based on the output of Step 1 of Algorithm 4 for all $i = 1, \ldots, C$.
2: Initialize $R = 0$, $BW = \sum(B^{(2)}(1 : s))$
3: for each chunk $i = 1, \ldots, C$ do
4: for each layer $n = 0, \ldots, a_i$ do
5: if $r_n < BW$ (chunk $i$ layer $n$ can be fetched by link 2) then
6: $BW = BW - r_n$
7: else
8: $R = R + r_n$
9: end if
10: end for
11: $BW = BW + \sum(B^{(2)}((i - 1)L + s + 1 : iL + s))$
12: end for
13: if $R > 0$ then
14: Initialize $LEFT = R$
15: for each chunk $i = 0, \ldots, C$ do
16: if $B^{(1)}(i) < LEFT$ then
17: $LEFT = LEFT - B^{(1)}(i)$
18: else
19: $B^{(1)}(i) = LEFT$
20: end if
21: end for
22: end if
23: end if

### V. Evaluation

#### A. Setup

To evaluate the performance of the proposed algorithms, we have built an emulation testbed, which is depicted in Fig. 1. The server, and the client nodes are both running in a Linux machine with kernel version 2.6.32, 24 CPU cores, and 32MB memory. The server and client communicate with each other via the loopback interface using the default TCP variant, TCP CUBIC. Two orthogonal links were created to emulate the behavior of the multi-path streaming. To fetch a layer of a chunk, the client sends a request for that layer to the server via one of the two links, determined by our algorithm, thus the server will send back the data packets of that chunk layer via the same link. The emulation ends when all chunks are received. We record the received time, and the actual number of layers received for every chunk. To introduce bandwidth variations into the emulated experiments, we adopt Dummynet running on the client side, thus the incoming bandwidth of the TCP packets from the server on the both links (i.e., 1 or 2) will be throttled according to the bandwidth datasets used. The bandwidth profile of the datasets for both the links are described later in this section. Finally, we introduce a delay of 60ms between the server and the client.

**Video Parameters:** The video used for the evaluation is Big Buck Bunny, which is published in [27]. It consists of 299 chunks (14315 frames), and the chunk duration is 2 seconds (48 frames and the frame rate of this video is 24fps). The video is SVC encoded into one base layer and three enhancement
layers. Table I shows the cumulative nominal rates of each of the layers. The rates on the table are the nominal rates, and the exact rate of every chunk might be different since the video is VBR encoded. In the table, “BL” and “EL\textsubscript{i}” refer to the base layer and the cumulative (up to) \textit{i}-th enhancement layer size, respectively. For example, the exact size of the \textit{i}th enhancement layer is equal to \text{EL}\textsubscript{i} - \text{EL}(i-1).

**Bandwidth Traces:** For bandwidth traces, we used two public datasets, representing the two paths. The first dataset (denoted Dataset1) consists of continuous 1-second measurement of throughput of a moving device in Telenor’s mobile network in Norway [38]. The second dataset (denoted Dataset2), is the FCC dataset [39], which consists of more than 1 million sets of throughput measurements. Both these datasets have been post-processed in [40] to give 1000 traces, each of 6-minute length which will be used in this paper for evaluations.

Dataset1 has higher average bandwidth than Dataset2, but it also has higher variance as it can be seen in Fig. 2(a–b). We use Dataset1 as traces for the first link while Dataset2 as traces for the second link.

**Algorithm Parameters** For the online version of the proposed algorithm (MP-SVC, and MP-Pref-SVC, described in Section III-E and IV), we set our algorithm’s parameters as follows. We choose \( W = 10 \) chunks, \( B_{\text{min}} = 4 \) seconds, and \( B_{\text{max}} = 2 \) minutes (60 chunks). We tried different buffer sizes, and the comparisons between different algorithms were qualitatively the same. Moreover, we choose \( \alpha = 2 \) seconds. We use the harmonic mean of the last 10 seconds (\( \beta = 10 \) seconds) to predict the future bandwidth. In other words, the predicted bandwidth for the entire window is set to the value of the harmonic mean of the last 10 seconds (or less in the start, when less data is available). Since there is no prediction at the beginning, the first two chunks are fetched at base layer quality where the first chunk is fetched over the first link, and the second one is fetched over the second link. For the link 2 preference case, we assume \( m = 0 \). Thus, link 1 is only used to avoid skips, and not to increase the quality of chunks beyond the base layer. Similarly for no-skip version, the key use of link 1 is to avoid/reduce stalls while not to improve further quality beyond the base layer. The proposed online algorithms without and with link 2 preference (MP-SVC, and MP-Pref-SVC, respectively) are compared with the following baseline algorithms.

**Multi-path, and SVC version of Buffer-based Approach (MP-BBA):** The authors of [12] proposed a buffer-based algorithm, BBA, for a single path and No-Skip streaming. BBA adjusts the streaming quality based on the playout buffer occupancy. Specifically, the quality depends on two thresholds. If the buffer occupancy is lower (higher) than the lower (higher) threshold, chunks are fetched at the lowest (highest) quality. If the buffer occupancy lies in between the two thresholds, the buffer-rate relationship is determined by lower thresholding the linear function between these extreme points to the available quality levels. We use the 30 and 90 seconds as the lower, and upper thresholds on the buffer length respectively. However, the standard BBA algorithm is a single path algorithm. In our proposed variant, MP-BBA, the quality is decided as per the BBA algorithm. In order to split layers across the two paths, the layers are split using the choice that minimizes the completion time of the chunk. Finally, we adapt this algorithm to the skip version where a chunk not downloaded before the deadline is skipped. The same modification to skip version is used for other no-skip versions described later. We note that the approach uses the SVC flexibility to split the layers across the two paths, and thus improves on the AVC version where each chunk will be fetched on only one path.

**Multi-path version of Buffer-based Approach using Multipath TCP (MPTCP-BBA):** This algorithm decides the quality based on BBA algorithm as described in MP-BBA.
However, these quality decisions are fetched using Multi-path TCP and the decision of splitting into paths is no longer needed.

**MPTCP-Pref-BBA** [13]: The authors of [13] proposed Multi-path Dash (MP-DASH) which is an Adaptive MPTCP Video Streaming Over Preference-Aware multi-path that takes the chunk quality decision based on BBA algorithm [12]. Even though [13] used AVC, the same decisions can be used for SVC.

**MSPlayer** [4]: MSPlayer takes quality decisions of the next two chunks based on the bandwidth prediction. Odd chunks are fetched on the first link, while even chunks are fetched on the second link. If the current bandwidth measurement of the slow link (link with lower predicted throughput) is larger than $(1 + \delta)$ times the estimated value, the chunk size is doubled and rounded to the nearest feasible chunk size. Similarly, if the current value is less than $(1 - \delta)$ times the estimated value, the chunk size is halved and rounded to the nearest chunk size. The size of the chunk which is to be downloaded using the fast link is adjusted based on the throughput ratio. In other words, its size is equal to the size of the chunk fetched over the slow link times the ratio of the predicted bandwidths of the two links. Finally, it is rounded to the nearest chunk size. We set $\delta$ to its default value (5%) [4]. We compare the proposed algorithms with MSPlayer only in case of equal priority since there is no known MSPlayer version where one link is more preferred over the other.

**MPTCP-Festive**: We use the default setting of Festive algorithm as described in [34] over the two links combined using multi-path TCP.

**MPTCP-Pref-Festive** [13]: The authors of [13] also considered a Preference-Aware algorithm based on Festive algorithm [34]. The decisions can be used over SVC.

**MPTCP-SVC and MPTCP-Pref-SVC Algorithms**: These are the variants of the online MP-SVC and MP-Pref-SVC algorithm, where Multipath TCP can be used, as described in Section III-E.

**off-MP-SVC and off-MP-Pref-SVC Algorithms**: These are the offline MP-SVC and MP-Pref-SVC as described in Section III where a genie-aided perfect bandwidth prediction is known for the entire video duration thus forming an upper bound of the performance (as measured by the proposed objective) of any online algorithm that splits layers on two paths.

**off-MPTCP-SVC and off-MPTCP-Pref-SVC Algorithms**: These algorithms run MPTCP-SVC with a genie-aided perfect bandwidth prediction is known for the entire video duration thus forming an upper bound of the performance (as measured by the proposed objective) of any online algorithm which may or may not use Multipath TCP.

### B. Skip Based MP-SVC Algorithm Without Preference

In this subsection, we will evaluate MP-SVC with a comparison to the baseline approaches in the skip based scenario. The results are shown in Fig. 3. The startup delay is chosen to be 5 seconds. Both the off-MP-SVC and off-MPTCP-SVC represent the optimal fetching policy without and with use of SVC.
multi-path TCP and thus represent the best possible strategies for the objective.

Fig. 3a shows the probability mass function of the number of chunks fetched at the different qualities (S=skips, corresponding to the chunks which were not fetched). The average playback rate among all traces, and the total number of skipped chunks among all videos is displayed on the top of Fig. 3a. We first see that MP-SVC significantly outperform the algorithms that do not use multi-path TCP (MP-BBA, and MSPlayer). For instance, about 50%, and 45% of the chunks are fetched at the $E_3$ quality in MP-BBA, and MSPlayer respectively. In contrast, the proposed algorithm MP-SVC fetches about 95% of the chunks at the $E_3$ quality. Further, MSPlayer runs into highest number of skips (366 chunks were skipped in total, which corresponds to 12 minutes of stall duration) while MP-BBA has 64 skipped chunks. In contrast, MP-SVC only has 24 skips, corresponding to less than 1 minutes of video playback. Another thing to note is that though MP-SVC is less flexible than MPTCP-SVC, MPTCP-BBA, and MPTCP-Festive due to the restriction of choosing a layer on only one of the links, yet, the Quality of Experience obtained in the MP-SVC is almost the same as compared to the MPTCP-SVC. Moreover, MP-SVC is better than MPTCP-Festive both in terms of avoiding skips and achieving higher average playback rate, and it outperforms MPTCP-BBA in the average quality (achieves 26% higher) with slightly higher number of skips. MP-SVC incorporates bandwidth prediction and the deadline of the chunks into its optimization based decisions, prioritizes the later chunks, and re-consider the decisions every 2 seconds. These properties help MP-SVC be adaptive to different bandwidth regimes and variations in the bandwidth profiles.

Fig. 3b shows the distribution of the layer switching rates (LSR), which is defined as $\frac{1}{C} \sum_{i=1}^{C} |E(X(i)) - EX\{X(i-1)\}|$ where $C$ is number of chunks and $E(X(i))$ is the expected play-back rate of $i$-th chunk, so if the $i$-th chunk is fetched at $n$-th enhancement layer quality, $E(X(i))$ will be equal to the nominal cumulative rate of the $n$-th enhancement layer. Intuitively, LSR quantifies the frequency of the layer change across the chunks and should be low for better quality of experience (QoE). MSPlayer performs poorly in terms of switching rate as compared to the other algorithms since it does not consider the buffer length and doubles or halves the quality based on the predicted bandwidth. MP-BBA also have higher switching rate. MPTCP-Festive is slightly better in terms of switching rate, while worse in the average quality and the skip durations.

Finally, we compare the online algorithms MP-SVC and MPTCP-SVC with the offline versions of them. We note from Fig. 3c that although, MP-SVC and MPTCP-SVC use prediction window of only 10 chunks (short window), and harmonic mean of the last $\beta = 10$ seconds for predicting future bandwidth, they achieve a fetching policy that is very close to the one achieved by the offline algorithm (perfect prediction for entire video duration) with slightly higher switching rate and a small increase in number of skips. The slight increase in switching rate for online schemes is in part since the first few chunks are downloaded in the base layer (because there is no bandwidth prediction initially), and a single jump from base layer to $EL_3$ contributes 1475/80 kbps/chunk, which is $\approx .02$ Mbps/chunk, to the LSR metric. Prioritizing later chunks, reconsidering the decisions every 2 seconds, and adjusting to prediction error, all help reducing the gap between the online and the offline algorithm.

C. Skip Based MP-SVC Algorithm with Link Preference

In this subsection, we will evaluate the proposed algorithms, MP-Pref-SVC and MPTCP-Pref-SVC, and compare them to the link preference based baseline approaches in the skip based scenario. The results are shown in Fig. 4. The startup delay is chosen to be 5 seconds. The algorithms off-MP-Pref-SVC and off-MPTCP-Pref-SVC represent the fetching policies when the bandwidth profiles are known non-causally without and with utilization of multi-path TCP, respectively.

Fig. 4a shows the probability mass function of the number of chunks fetched at the different qualities. We first note that there is no algorithm that fetches a chunk from a single path to compare with. Thus, we compare the algorithms with the versions that use multi-path TCP even though that is a disadvantage to MP-Pref-SVC since it does not use multi-path TCP. We see that MP-Pref-SVC achieves 15% higher average playback rate than MPTCP-Pref-Festive with less number of skips, and about 6% higher average playback rate than MPTCP-Pref-BBA with slightly higher number of skips. On the other hand, MPTCP-Pref-SVC algorithm outperforms both MPTCP-BBA and MPTCP-Festive both in terms of the achievable average playback rate and the number of skips. However, when one of the link is preferred, not only is the average playback rate important, but the bandwidth of link 1 used is also important. Thus, in Fig. 4b, we plot the CDF of link 1 usage (L1Usage), and the total amount of link 1 usage per chunk is also displayed above the figure. We see that both MP-Pref-SVC and MPTCP-Pref-SVC use lower amount of link 1 bandwidth as compared to MPTCP-BBA and MPTCP-Festive. In about 80% of the bandwidth traces, MP-Pref-SVC and MPTCP-Pref-SVC used link 1 to fetch only one chunk, and that chunk is necessary at the beginning to predict the available bandwidth of link 1 (the offline algorithms did not use link 1 for 80% of the traces). However, both MPTCP-BBA and MPTCP-Festive used link 1 to fetch more than 1Mb/chunk for 50% of the bandwidth traces. Thus, the proposed algorithms give comparable or better average qualities than the baselines with significantly lower utilization of link 1.

D. No-Skip MP-SVC and MP-Pref-SVC Algorithms

In this subsection, we evaluate our proposed algorithms for the No-Skip based scenario. The initial startup delay is chosen to be the minimum of 5s and the download time of the first chunk while the other parameters are the same as in the skip-based version. The results are shown in Fig. 5. The average playback qualities and the overall stall durations over all videos are shown above the sub-figures. The first thing to note is that the layer distribution results are very similar to that in the skip based scenario for all the algorithms. The
main difference in the no-skip version is that since there are no skips, the video may have multiple stalls. Thus, in Fig. 5, we give the duration of stalls (re-buffering time) rather than skips. We omit the c.d.f. of the layer switching rate and the LTE usage figures since the results are qualitatively similar to that in the skip version. We however give the average link 1 usage above Fig. 5b. We see that MPTCP-SVC and MPTCP-Pref-SVC outperform all other baseline algorithms in all the considered metrics both when the link 2 is preferred or when both the links have similar preference. Further, MP-SVC and MP-Pref-SVC have slightly higher stalls than the MPTCP variants with the other metrics being very close. It can also be seen that MP-SVC outperforms the baseline algorithms that do not use MPTCP (MP-BBA and MSPlayer) in all the considered metrics.

VI. CONCLUSIONS

This paper provides an adaptive streaming algorithm for a video encoded with Scalable Video Coding (SVC) over multiple paths, where each layer of every chunk can be fetched from only one of the paths. The problem of optimizing the user's quality of experience (QoE) is formulated as a non convex optimization problem. It is shown that this non convex problem can be solved optimally with a complexity that is quadratic in the video length. Further, an online algorithm is proposed where several challenges including bandwidth prediction errors are addressed. The proposed algorithms are further extended when one of the link is preferred over the other. Extensive evaluations with real traces of public dataset reveal the robustness of our schemes and demonstrate their significant performance improvement compared to other state-of-the-art multi-path algorithms.

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APPENDIX A

PROOF OF RESULTS IN SECTION 3.4

A. Proof of Lemma 2

We first note that using the MP-SVC algorithm, nth layer of chunk \( i_s \) is skipped in two scenarios, which are described as follows.

Case 1: If \((n-1)\)th layer of the chunk \( i_s \) is not fetched, then \((n)\)th layer of the chunk \( i_s \) can not be fetched due to constraint (4).

Case 2: The residual bandwidth in any of the connections, ignoring the bandwidth used to fetch up to \((n-1)\)th layer of chunks less than \( i_s \) (lower layer decisions) and the bandwidth used to fetch up to nth layer of chunks greater than \( i_s \) (current layer decisions for later chunks), is not enough to fetch chunk \( i_s \). In this case, the bandwidth is not enough to obtain the chunk \( i_s \) when using backward algorithm.

Mathematically, let \( \pi_p^{(1)} \) and \( \pi_p^{(2)} \) be the bandwidth reserved to fetch up to \((n-1)\)th layer of chunks \( < i_s \) over first and second links respectively, and \( \pi_i^{(1)} \) and \( \pi_i^{(2)} \) be the bandwidth reserved to fetch up to nth layer of chunks \( > i_s \) over links 1 and 2 respectively. Since decision of the current layer size starts from back, then the nth layer of the chunk \( i_s \) is skipped when:

\[
\sum_{j=1}^{\text{deadline}(i_s)} B^{(k)}(j) - \pi_p^{(k)} - \pi_i^{(k)} < Y_n \forall k = 1, 2
\]  

We note that the MP-SVC algorithm assigns a layer to the link that leaves more bandwidth for fetching the earlier ones. Therefore, the available bandwidth to fetch nth layer of a chunk can’t be higher than its value using MP-SVC algorithm unless nth layer of a chunk with higher index was skipped. We will now show that MP-SVC algorithm has no larger skips at any layer (given previous layer quality decisions) as compared to any other feasible algorithm.

Skips which are due to Case 1 will be the same for any feasible algorithm. Thus, we do not consider skips that are of Case 1. For the skip of Case 2, we first consider the last skip by our algorithm. We note that since the MP-SVC algorithm will fetch a nth layer of any chunk if at all possible, if there is a skip at \( i_s \), any algorithm will have a skip for a chunk \( i \geq i_s \). Further note that skipping nth layer of chunk \( i_s \) as compared to nth layer of chunk \( i \) will allow for more bandwidth till deadline of the earlier chunks. Thus, if there is another skip using the MP-SVC algorithm, there must be another skip at or after the time of that skip in any other algorithm. Thus, we see that the number of skips in any feasible algorithm can be no less than the proposed algorithm.

B. Proof of Lemma 2

We note that the proposed algorithm brings all nth layer skips to the very beginning (if necessary, it skips the earliest ones). We note from Section A-A that if the ordered set of nth layer skips for the backward algorithm are \( i_1, i_2, \cdots, i_H \) and for any feasible algorithm with same number of nth layer skips are \( j_1, j_2, \cdots, j_H \), then \( i_k \leq j_k \) for all \( k = 1, \cdots, H \). Earlier nth layer skips help get the higher bandwidth available for future chunks thus proving the result in the statement of the theorem. Any other feasible algorithm with larger number of nth layer skips will achieve smaller objective when \( \gamma \) satisfies (1), thus showing that it will not be optimal.

C. Proof of Theorem 1

The result follows by recursive use of Lemmas 1 and 2. Use of Lemma 1 shows that the proposed algorithm is optimal for base layer skips. According to lemma 2 running MP-SVC algorithm offers the maximum bandwidth per chunk for next layer decisions among all feasible algorithms with same number of skips. Therefore, the bandwidth profile that is passed to \( E_1 \) scan is the maximum per chunk. Running MP-SVC algorithm on \( E_1 \) layer would produce optimal BL and \( E_1 \) decisions by Lemma 1. Keep scanning sequentially up to Nth layer would yield optimal solution to the optimization problem (9) when \( \gamma \) satisfies (1), and that concludes the proof.

APPENDIX B

OPTIMALITY OF NO SKIP BASED STREAMING ALGORITHM

The following lemma states formally that the No-Skip MP-SVC algorithm achieves the minimum stall duration such that all chunks are at least fetched at base layer quality.

Lemma 3. If \( \text{deadline}^*(C) \) is the deadline of the last chunk \( C \) that was found using No-skip MP-SVC algorithm such that all chunks can be at least delivered at base layer quality, and \( \text{deadline}'(C) \) is the deadline of the chunk \( C \) that was found using any other algorithm, then:

\[
\text{deadline}'(C) \geq \text{deadline}^*(C).
\]

In other words, No-Skip MP-SVC achieves the minimum stall duration such that all chunks are fetched at least at base layer quality.

Proof. The proposed algorithm is a greedy algorithm that only adds to the deadline if there must be a skip due to not enough bandwidth. Further, the algorithm fetches all the chunks at only base layer quality which would have the lowest possible fetching times. Due to this greedy nature, no other algorithm can fetch all the chunks before those obtained by this greedy algorithm.

Having shown the minimum stall durations, Theorem 1 shows that the MP-SVC algorithm is optimal for the proposed No-Skip problem when \( \gamma \) satisfies (1).

APPENDIX C

OFFLINE PROBLEM FORMULATION FOR SVC VIDEO STREAMING WITH LINK PREFERENCE

In addition to the objectives mentioned without link preference, we further consider minimization of the link 1 usage. In order to account for the third objective of minimization of link 1, we consider a parameter \( m \in \{0, \cdots, N\} \) indicating that the link 1 should not be used to obtain chunks above layer \( m \). This will help using link 1 to help improve getting lower
Lemma 4. None of the layers is fetched using link \( m \) layer greater than 1. Suppose that layer \( n \) is to be fetched and the additional cost function satisfies (18). Thus, it is better not to fetch chunk \( i \) at layers \( n \) and higher if this layer is to be fetched using link 1.

Thus, Link 1 can only be used to fetch chunks at the layers till layer \( m \). However, among any two strategies that achieve the same number of chunks at all layers till layer \( m \), the proposed problem formulation will choose the one with lower Link 1 usage. This is given in the following lemma.

Lemma 5. Among two strategies with the same layers fetched for every chunk for layers from 0 to \( m \), the one that obtains lower content over link 1 is preferred.

Proof. For the same possible chunks till layer \( m \), the minimum extra usage of link 1 is \( \Delta \). Thus, as long as the additional cost of this Link 1 usage is more than all the benefits of the layers above \( m \), the cost will outweigh the benefit. Since this holds by (19), the result holds.

Finally, we note that choosing link 1 for layers from 0 to \( m \) will have positive utility since \( D < 1/\gamma \). Finally, we need to show that if an extra chunk can be obtained at a layer \( n \leq m \), the above problem will not be constrained by the cost of using link 1. This is satisfied due to (18). More formally, the following holds.

Lemma 6. Among two strategies with the same number of chunks at layer 0, \( k \) for \( k < m \), the strategy that obtains the largest number of chunks in layer \( k + 1 \) achieves better objective.

Thus, we see that the utility function for the above choice of range of \((D, \gamma)\) satisfies the properties needed for the formulation.

Even though we do not have a general algorithm that optimizes this proposed formulation for any value of \( m \), the proposed algorithm MP-Pref-SVC in Section VI is optimal when \( m = 0 \). Thus, when the objective is only to use link 1 to avoid skips, the proposed algorithm is optimal. This is easy to see using Lemma 5 that the proposed algorithm satisfies this condition. Thus, all the conditions of optimality of the additional cost function are satisfied. The key reason this does not hold for general \( m \) is the greedy policy of Link1-Save algorithm in Algorithm 5. It is not necessary for a general \( m \) that this strategy will use minimum amount of link 1.

Finally, we note that when MPTCP can be used, the key difference is that the constraint (1) is removed. Thus, when partial fetching is allowed, the modification of Link1-Save will use minimum link 1 and thus all the conditions are satisfied for any \( m \). This proves that the proposed algorithm is optimal for all values of \( m \), when MPTCP can be used. We further note that the decisions made using this algorithm can be used for both SVC and AVC when MPTCP can be used.