A New Multi-path Selection Scheme for Video Streaming on Overlay Networks

Zheng Ma*
Department of Computer Science, Yale Univeristy
New Haven, CT, USA
zhengma@cs.yale.edu

Huai-Rong Shao, Chia Shen
Mitsubishi Electric Research Laboratories
Cambridge, MA, USA
{shao,shen}@merl.com

Abstract—This paper presents a new multi-path selection scheme for video streaming on overlay networks. Our scheme uses an overlay network architecture that makes minimal assumptions about the knowledge of the underlying network. We first propose a new QoS metric link correlation and a path correlation model for multi-path selection problem. After discussing the tractability of minimal correlation multi-path selection problem, we present an efficient algorithm called correlation cost routing to select multi-path in overlay networks. The simulation results show that the average peak signal-to-noise ratio (PSNR) of the transmitted multiple descriptions coding (MDC) video using our multi-path selection algorithm improves by up to 3.2 dB over maximally link-disjoint multi-path selection method. Furthermore our new algorithm is more efficient than previous methods since it shares the same complexity with Dijsktra algorithm.

Keywords— Path diversity, overlay networks, QoS routing, multi-path selection, NP-hard.

I. INTRODUCTION

Recently, various techniques have been proposed to improve end-to-end streaming media quality by using special coding technique and path diversity. For example, multiple description coding (MDC) [2],[3] and Fine-Granularity-Scalability (FGS) partitioning [4] are two such schemes. These coding schemes work particularly well on uncorrelated paths in which it is unlikely that the network paths simultaneously suffer from packet losses. While most of the previous work focuses on how to generate multiple related sub-streams, efficient multi-path selection methods to achieve good path diversity have not been fully investigated in the literature.

Some latest results on multi-path selection for MDC video streaming on overlay networks are shown in [5] and with improvements in [6]. Ali et al. [5] studied how to select multi-path that maximizes the *average* quality of video at clients on an envisioned overlay framework. They also provide a theoretical end-to-end distortion model for MDC video and select the optimal path pair that minimizes the overall end-to-end distortion. In this paper, we solve the problem of how to select multi-path that maximizes the *worst* video quality at clients on a simpler envisioned overlay framework with minimal knowledge of and support from the underlying infrastructure. We also propose an efficient algorithm, the correlation cost routing algorithm, to find such paths.

Content Delivery Networks (CDN) has been used to provide path diversity for MDC video streaming. John et al [1] use existing CDN infrastructure to exploit different network paths between clients and its nearby edge servers. They give a model to select the optimal pair of servers with complementary descriptions for a client. The video files may be pre-stored in several servers across the network. We can also use CDN in our proposed scheme. However, we do not require the CDN servers to pre-store the video descriptions and other complicated support. Thus, by introducing our multi-path selection scheme, we also introduce a new service model for existing CDN to provide Internet video streaming with path diversity.

We'll discuss the path diversity in overlay networks and our new overlay architecture for Internet video streaming first in next section. Then we present the proposed new QoS metric in Section III and the new multi-path selection algorithm in Section IV. Simulation results are showed in Section V compared with totally link-disjoint paths or maximally link-disjoint paths discussed in [1], [5]. Finally, Section VI concludes the paper.

II. PATH DIVERSITY IN OVERLAY NETWORKS

An overlay network [7] is a virtual network built over an existing network as substrate (Fig.1). A link is a logical connection between two overlay nodes. In a typical overlay network, overlay nodes keep good links among each other by periodically probing their neighbors. Overlay networks offer several features that make them useful to deploy new services over current Internet. The first feature is that an overlay network consists of a cooperative group. The overlay nodes ("O-nodes") can form their own protocol by application-layer routing without any support from underlying infrastructure. The application-layer routing may obtain better reliability and even better delay as observed by the author of [7] in their measurements. The second feature is that an overlay network can be transparent to the physical network. A third feature of overlay networks is that most overlay nodes only know the end-to-end measured information of the logical connections

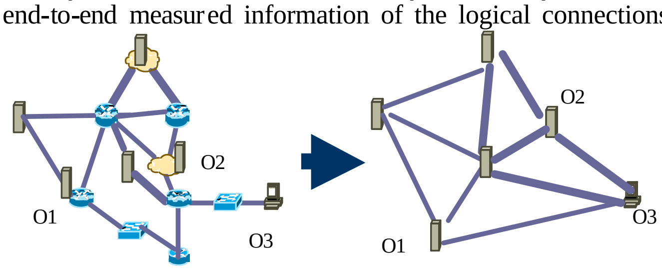

Fig. 1 Overlay network example

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between them but don't know the underlying physical network 's information like topology and loss rate.

Using overlay network to provide Internet video streaming has been proposed in [5]. However, these systems require support from underlying network and are not totally transparent to the underlying infrastructure. In this paper, we propose to use the following overlay network architecture that makes minimal assumptions about the knowledge and support of the underlying network: Overlay servers are placed at the edge of the network. These servers have both high downlink and uplink bandwidth. They will act as overlay nodes ("O-nodes") in the video streaming service. These servers together with the video server consist of an overlay network and maintain a topology by periodical probing. Our architecture does not require much local storage at the O-nodes. It only uses the bandwidth contribution of each O-node. This architecture also gives us a new Internet service model that we call "overlay forwarding" service. In such a model, the existing commercial servers in the Internet such as CDN servers [8] can provide a new "overlay forwarding" service for the video server. They act as O-nodes for a video server and maintain an overlay network with the server (it can be the usual CDN topology). Whenever the video server receives a request from a client, it will use multiple paths to deliver the video to the client using the overlay network. This is a more practical solution than the method that requires the CDN servers to pre-store the video files [1]. Because the current CDN service providers charge the service by the capacity of local storage, pre-stored video service may not be affordable by most customers [8]. It is a realistic service model both technically and economically. Fig.2 is an illustration of such an Internet video streaming system.

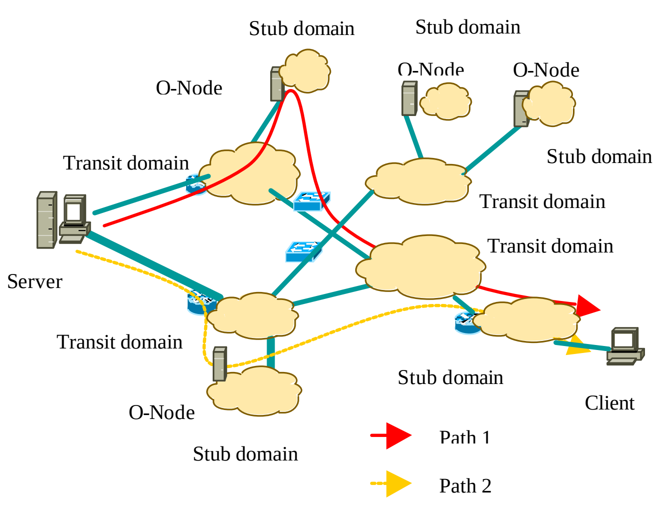

Fig.2. Multi-path video streaming using CDN servers

Path diversity in an overlay network has very different properties as in a physical network. A link in an overlay network can be mapped onto a physical path consisting of multiple physical links. Two links in an overlay network are not necessarily uncorrelated. For example, in Fig.1, the overlay link O1O3 and O2O3 share some physical links and thus have correlation in properties such as loss rate and delay. How to select multi-path in such a network taken into consideration of the link correlation is still an open problem. Some previous path selection algorithms such as maximally link-disjoint path method [1] [5] simplify the correlation between paths as jointness and may not work well in some cases. Because they can only use good links in the network once and tend to use the longer path. Our solution to this problem is twofold. First we propose a new QoS metric describing link correlation and a path correlation model for the multi-path selection problem. Second we give an efficient algorithm to select multi-path based on this model. We will elaborate the new QoS metric and path correlation model in next section.

III. Link Correlation Metric and Path Correlation Model

A. *Link Correlation Metric*

In our new overlay video streaming architecture, the video server in the envisioned overlay network maintains the link correlation metric for every two links. Because we do not assume the knowledge of the underlying physical network topology, we use the statistical information of each link collected at the server to define their correlation as a new QoS metric in (1):

$$Cr(L_{ij}, L_{mn}) = \frac{E[(L_{ij}-\overline{L}_{ij})(L_{mn}-\overline{L}_{mn})]}{\sqrt{E(L^2_{ij})-(\overline{L}_{ij})^2}\sqrt{E(L^2_{mn})-(E(\overline{L}_{mn}))^2}} \quad (1)$$

Here L_{ij} and L_{mn} are the metric for link *i-j* and link *m-n* as a random variable. It can be any metric we are interested in. For example, loss rate may be a good metric for multi-path selection problem. Here, $\overline{L}_{ij} = E(L_{ij})$. All the expectations and $Cr(L_{ij}, L_{mn})$ are calculated within some time window. This formula is based on the standard correlation definition of two random variables in statistics. Every O-node periodically updates their local link information by probing their interested metrics. This information can be periodically updated and piggybacked to the video server with the usual routing packets. The video server will set a time window size and also periodically update the correlation information between links according to (1). Fig.3 is an example of this procedure. In addition to the correlation matrix, the server will also have other existing link metrics of the envisioned overlay network like latency, available bandwidth and loss rate.

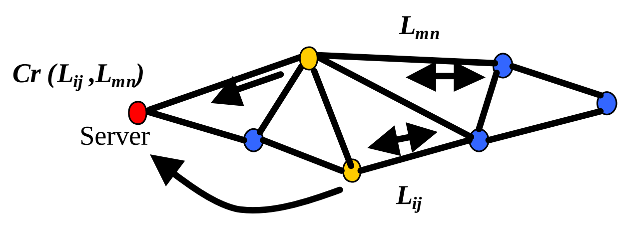

Fig.3 Example of an envisioned overlay network

B. *Path Correlation Model*

The path correlation model is based on the new QoS metric. Let Path A and Path B are two paths in the overlay network with link set A and B. The correlation of them is defined as (2):

$$Cr(A,B)=\frac{Cov(A,B)}{\sqrt{Var(A)}\sqrt{Var(B)}} \quad (2)$$

In which :

$$Cov(A,B)=\sum_{a\in A}\sum_{b\in B}Cov(a,b)$$

$$Cov(a,b)=Cr(a,b)\cdot\sqrt{Var(a)}\sqrt{Var(b)}$$

$$Var(A)=Cov(A,A)=\sum_{a_i\in A}\sum_{a_j\in A}Cov(a_i,a_j)$$

Here, we assume :

$$A=\sum_i a_i \quad B=\sum_j b_j$$

The new metric will work well with additive[1] metrics. This new metric together with traditional QoS constraints such as latency and loss rate can be used to select the multi-path in the network. The path correlation model gives us a quantitative measurement of overlay path correlation other than the static overlay jointness information. In multiple descriptions encoded video, the worst effect at the clients would happen when all descriptions are missing. So minimizing the correlation of multi-path would maximize the performance of worst case of overlay video streaming. That's why we are trying to maximize the *worst* scenario of video quality. Here, our optimization objective is different from [5], which tries to maximize the *average* performance of video streaming.

C. Minimal correlation multi-path selection problem

With our new path correlation model, the multi-path selection can be formulated as an optimization problem. In the following descriptions, we focus on selecting two paths. Similar to [9], we used edge based formulation of the multi-path selection problem. Here, we only show an example of the formulation of two paths selection problem. Formulation of more paths selection problem can be obtained easily as this example shows using more indication variable vectors for each path and more constraints for each flow. The network is represented by a graph *G=(V, E)*, where *V* is the set of nodes and *E* is the set of links. Each link $(i,j)\in E$ is associated with R non-negative and additive QoS values $W_r(i,j), r=1,2,...,R$, there are R corresponding path QoS constraints $D_r, r=1,2,...,R$; the correlation between link (i,j) *and* (m,n) as defined in (1) is $Cr(L_{ij},L_{mn})$. Also we defined indication variable vector X=(…X_{ij}…) and Y=(…Y_{ij}…) to indicate whether a link (i,j) is in the first path (X_{ij}=1), and in the second path (Y_{ij}=1). To show the complexity of selecting the minimal correlation multi-path, we will use the following simplified definition of overlay path correlation in our proof: $Cr(A,B)=\sum_{a\in A}\sum_{b\in B}Cr(a,b)$. For the simplified definition of path correlation, we can write the minimal correlation multi-path selection problem as following:

$$\text{Minimize} \sum_{(i,j)\in E}\sum_{(m,n)\in E}X_{ij}\cdot Y_{mn}Cr(L_{ij},L_{mn}) \quad (3)$$

$$\text{Subject to:} \quad X_{ij}\in\{0,1\}, Y_{mn}\in\{0,1\}, \forall(i,j)\in E$$

$$\sum_{(i,j)\in E}X_{ij}W_r(i,j)\le D_r, \forall\, r=1,2,...,R \quad (4)$$

$$\sum_{(i,j)\in E}X_{ij}-\sum_{(j,i)\in E}X_{ji}=\begin{cases}1, & if\ i=s\\ -1, & if\ i=d\\ 0, & else\end{cases} \quad (5)$$

$$\sum_{(m,n)\in E}Y_{mn}-\sum_{(n,m)\in E}Y_{nm}=\begin{cases}1, & if\ m=s\\ -1, & if\ m=d\\ 0, & else\end{cases} \quad (6)$$

Here, (4) means the R different QoS constraints. (5) and (6) are flow constraints.

Theorem 1: The minimal correlation multi-path selection problem is NP-Hard.

Proof: To prove this is an NP-hard problem, we can rewrite this integer programming formulation of the problem as the following: Define new matrix $C_{|E|\times|E|}$ that has $Cr(L_{ij},L_{mn})$ as entries. Define new vectors $P_{2|E|\times 1}=\begin{pmatrix}X\\Y\end{pmatrix}$ and $D_{2|E|\times 2\times|E|}=\begin{pmatrix}0 & C\\ C^T & 0\end{pmatrix}$. Then change the corresponding constraints (4)-(6) with respect to the new variables, the minimization objective would become $\frac{1}{2}P^TDP$. Now, this is in the standard format of Quadratic Programming, which is a NP-Hard problem as proved in [10]. So the minimal correlation multi-path selection is intractable.

IV. MULTI-PATH SELECTION ALGORITHM

The NP-hardness of the minimal correlation multi-path selection problem requires us to look for a heuristic solution for the problem. We propose a new efficient algorithm to solve the multi-path selection problem. Our algorithm, as described in Fig. 4, will update all the link metrics of the network graph after finding one path and then find the next path based on the new graph. To take into account the correlation between links, we introduce a new cost for each link L with respect to previous chosen path set S called correlated cost (cc) in (7)

$$Cr_S^L=\sum_{S_i\in S}Cr(L,S_i) \quad (7)$$

The correlated cost of link *L=(i ,j)* with chosen each chosen path S_i is calculated as (2). Then we use the following cost

[1] The additive QoS metric means that the path metric is the summation of the metric of each segment in the path. Examples of additive QoS are latency, delay jitter and etc. Some non-additive QoS metric like loss rate can be transformed to an additive metric using a function like log. See [13] for details.

function (8) to combine the new metric and the R traditional metrics that we are interested in together to get a new cost for each link.

$$Cost_S^L = a \cdot Cr_S^L + \sum_{i=1}^{R} a_i W_r(i, j) \qquad (8)$$

Here, a and a_i are proper scaling factors to balance these metrics.

Step 0. Invalidate all the links in the networks with available bandwidth less than the targeting streaming rate.

Step 1. Find the first shortest path based on latency or loss rate.

Step 2. Update the available bandwidth of each link by previous chosen paths. Invalidate the links with available bandwidth less than targeting streaming rate.

Step 3. Calculate the new Correlation Cost for each link with respect to the chosen links.

Step 4. Using the cost function to combine the new correlation metric and other metrics into a new cost for each link.

Step 5. Find the shortest path based on the new cost (using Dijsktra algorithm)

Repeat step 2 –5 until find all paths we need.

Fig.4 Correlation Cost Routing for multi-path selection

After finding the first shortest path based on the traditional link metric such as bandwidth, latency and loss rate for multimedia applications, we use correlation cost as another constraint to calculate the new shortest path. To find one path that satisfy multi-constraint, we use the cost function that tries to combine the correlation cost and the other most important metrics like loss rate and latency (using appropriate scaling factor) into one single cost. Then use *Dijsktra* algorithm to find the next path according to the new cost. Thus our algorithm has the same complexity as Dijsktra algorithm. Because finding one path with general multi-constraint is known as a NP-hard problem [11], we use our heuristic in (8) to achieve high performance in multi-constraint multi-path selection. Various approximation algorithms for multi-constraint path selection have been proposed [12]. Our algorithm can use them as a procedure (replacing step 4 and 5) to get a more accurate solution but increase the computation complexity. Interested readers are referred to [11], [13].

V. Simulation Experiments

We conducted simulation experiments to study how our algorithm behaves for real-time video streaming applications on overlay networks. The simulation results are to show the effectiveness of the proposed correlation cost routing algorithm. The goal of the simulation is to find how much improvement the correlation cost routing multi-path for MDC streams is able to yield over maximal link disjoint paths for MDC streams and shortest path for single description (SD) streams.

A. Methodology

In the simulation, we conducted several tests on several standard test sequences to stream from a server to a client. Here, we will show the results for FORMAN sequence. All the other simulations were observed with similar results. We used PSNR (peak-signal-to-noise-ratio) of each frame defined as $PSNR = 10 \times \log_{10}(\frac{255^2}{MSE})$ to make a comparison. The MSE is the mean square error between corresponding pixels in the each frame.

The single description (SD) and multiple descriptions (MD) encoded streams were produced with a standard MEPG-2 encoder at 140Kbyte/s. We used time-domain partitioning method with two descriptions for its simplicity and a simple concealment technique that uses the corresponding frame in the neighboring frames (the other description in the MD case) or just repeated the information from the last available frame. Here because we focused on the network support part for the overlay video streaming system, we didn't rely on any particular video encoding scheme or concealment technique that would increase the stream quality if applied.

B. Internet and overlay topology

We used GT-ITM [14] to generate transit-stub graph model as Internet topology in our experiment. The topology consisted of 240 nodes with 4 mesh-connected transit domains, 10 nodes per transit domain, 1 stub per transit node and 5 nodes in a stub domain. We used a similar set up for Internet as the simulation of [5].

The link capacity for the simulated Internet is assigned as following: 1.0 Gbps to transit-to-transit edges; 100 Mbps to transit-to-stub edges; 2-5 Mbps for stub-to-stub edges. The available bandwidth on each link is chosen randomly in the range of 20%-80% of its capacity. The packet loss rates were randomly assigned proportional to the link utilizations in thee range of 0.1%-1% for all links except one link in each domain, whose loss rate was randomly chosen as 10%-20% to emulate congestion. Each transit-domain link was assigned delay in the range of 10-30ms. Each stub-domain link was assigned delay between 5-10ms. Finally, all links are assigned a delay jitter between 0-10ms to introduce exponentially distributed jitter for each packet.

For the overlay topology, we used random graph model to generate the topology with size 10 and 20. We randomly mapped the overlay nodes to the nodes in the physical network except the transit nodes that are core routers or switches. The Internet path of each overlay link was calculated using the shortest path (by hop) between two overlay nodes. Then the overlay link metrics like latency, loss rate, available bandwidth and so on are calculated using the metrics of the Internet path to which this virtual link mapped.

C. Simulation results

We compared three different video streaming methods on the overlay network, the shortest path for SD, maximal link-disjoint path routing and correlation cost routing for MD. A video server and a client were randomly selected among the overlay nodes. For the single shortest path method, we first selected the paths with the minimum number of hops and if there are several paths with equal number of hops, we chose the one with minimum end-to-end delay. SD encoded video was sent along the shortest path. In the maximal link-disjoint path routing method, we generated all possible path pairs between server and client. We find the pairs with minimum number of overlapping links and then chose the pair with minimum total end-to-end loss. For the correlation cost routing method, we first set up the correlation matrix at the server and then used the correlation cost routing algorithm to find the two paths. In the last two methods, MD encoded video was sent along the two selected paths simultaneously.

We ran 10 simulations for different overlay topologies and network conditions. For each simulation we repeated with different random seed 100 times to obtain statistically reliable result. The summary of the results is in table I. From the results, we can see that our correlation cost routing method considers the correlation between overlay links into path selection procedure and have a better PSNR. As stated before, in our method the good links can be used twice and thus packets meet the delay constraint more likely than maximally link-disjoint paths.

We also draw the distribution of the individual frame qualities of a typical run of the simulations in Fig. 5. We can see, the SD stream video suffered a lot from burst lost in the network because the lack of path diversity. Maximally link-disjoint paths mitigated the problem in some cases; however, because the disjoint overlay path may still share some Internet links, the method also suffered from the burst loss some times. Finally, the correlation cost routing gave us the best performance among the three.

VI. Conclusion and Future Work

In this paper, we presented a new multi-path selection scheme for MDC video streaming using an envisioned overlay network over the Internet. We proposed a new QoS metric, link correlation metric. We also provided a path correlation model for multi-path selection problem on overlay network. After proving the minimal correlation multi-path selection problem is a NP-hard problem we gave an efficient multi-path selection algorithm called *correlation cost routing* to find multi-path in overlay network. Simulation results showed that our approach improved the performance of previous maximally link-disjoint paths by up to 3dB. The future work would be implementing the scheme in the Internet and measure its performance in real world.

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Table I: Simulation results for the FOREMAN sequence

	Single Path		Max Link Disjoint		Minimal Correlated	
Run #	PSNR	Lost/Delay	PSNR	Lost/Delay	PSNR	Lost/Delay
1	30.86	16/3	32.63	8/6	34.15	6/4
2	31.63	14/2	33.21	6/4	34.54	6/2
3	28.51	44/4	30.87	16/7	32.98	8/4
4	29.01	38/2	31.24	14/5	33.23	6/4
5	25.83	58/5	28.86	35/8	31.64	13/7
6	28.07	36/4	30.54	17/5	32.76	8/4
7	27.80	48/6	30.33	15/6	32.62	9/5
8	28.64	30/4	30.96	17/7	33.04	8/4
9	30.25	18/2	32.18	8/6	33.85	8/4
10	33.27	8/2	34.44	6/2	35.36	4/2
Average	29.38	31.0/3.4	31.52	14.2/5.6	33.41	7.6/4.0

Fig.5 FOREMAN simulation #3