EMPIRICAL STUDY ON MULTI-PATH BENEFITS ON INTERACTIVE VIDEO

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ABSTRACT

The oncoming prosperity of interactive multimedia application triggers significant challenge to current best-effort Internet because of the dynamic and unpredictable available bandwidth, end-to-end delay, and packet loss. Recently, overlay technique has emerged as an approach to help mitigating these problems. In order to understand the potential benefits of using multi-path provided by overlay network to interactive video, this paper examines the performance of two special multi-path deliver schemes — dual-path mesh and dual-path round robin, and compares their metrics of round-trip delay, packet loss, one-way delay jitter to the direct Internet path by analyzing 7 days of data collected from 102 geographically diverse PlanetLab nodes. By mapping the collected data with MPEG-4 coded "Foreman" video sequence, the paper also presents multi-path benefit on peak signal-to-noise ratio (PSNR).

1. INTRODUCTION

Nowadays, the widespread use of the Internet, increasing power of personal computers and advance of digital video technology have fueled the deployment of various interactive multimedia applications in the Internet, such as video telephony, distance learning and telemedicine. These applications' stringent requirements on bandwidth, end-to-end delay and loss rate are triggering unprecedented challenges to current Internet. Recently, the prevalence of broadband Internet connection technologies such as ADSL modems, cable modems, and T1 lines makes the bottleneck of video delivering from the constrained last-mile bandwidth shifting upstream to the backbone, peering links, and the best-effort Internet [1], which makes interactive video communication via multi-path of overlay network become practical and prospective.

To develop a fundamental understanding of the multi-path benefit to interactive video over wide-area networks, this paper experimented two simple but effective multi-path delivering schemes, namely dual-path mesh (DPM) [2] and dual-path round robin (DPRR) [3] on PlanetLab [4]. DPM duplicates all the packets along different paths, while under DPRR, each of the two paths carries half traffic and packet transmission is carried out in a round robin manner, for example, odd numbered packets are transmitted along path 1 while even numbered packets are transmitted along path2.

Video error control and concealment techniques are beyond the scope of this paper, it is hoped however, that the results of this paper will be valuable in guiding the design of more effective error control and concealment techniques. Besides, this paper concentrates on video because it places the greatest load on the network in terms of bandwidth, as well as delay and packet loss. It is not difficult to extend the results of this work to voice.

The remainder of this paper is organized as follows: Section 2 describes the methodology of the experiment. Section 3 to 5 compare the performance of single path and multi-path from the network parameters: round-trip delay, packet loss, and one-way delay jitter, respectively. Section 6 investigates their behavior differences in the metric of PSNR. Section 7 concludes the paper.

2. EXPERIMENT

From Nov. 8th 2006 to Nov 14th 2006, three types of measurement daemon: *sender*, *forwarder*, and *receiver* were run in the experiment, where a *sender* sent UDP packets with timestamp and sequence number directly to a receiver, or sent such packets to one of the *forwarders*, which relayed the packets to the *receiver*. The former is called single direct path (SDP), while the latter is called single indirect path (SInP). Both DPM and DPRR are composed of one SDP delivering and one simultaneously SInP delivering. When receiving a packet, the *receiver* recorded the time at which it was received and stored this along with the source timestamp and sequence number in a trace file. From the trace files, one way delay jitter and loss statistics along various paths could be reconstructed offline. Ping scripts were also run but at a lower frequency of approximately once every 3 minutes to measure round-trip time (RTT).

The above programs are installed on 102 PlanetLab nodes, including 40 *senders/receivers* and 62 *forwarders*, scattered in 81 sites, 22 countries and 5 continents (see Table 1). It is not claimed that the selected nodes are representative of the

Table 1. Distribution of the Selected Nodes

North America	Europe	Asia	South America	Oceania	com/ org/net
26	24	19	5	3	25

Table 2. Average Packet Loss Rate (%)

Bit Rate	SDP	All DPM	All DPRR	Best DPRR
128Kbps	1.01	0.26	1.09	0.41
256Kbps	1.66	/	1.63	0.57
384Kbps	2.07	0.67	1.99	0.77
768Kbps	2.75	/	2.44	1.29
1Mbps	3.78	1.18	2.90	1.82
2Mbps	4.50	/	3.91	2.31

Internet as a whole. However, the 111 SDPs and 5928 DPMs/DPRRs do provide a diverse topology for our study.

During 7 days time, each SDP, DPM and DPRR ran the same packets transmission 6 times at different period of time to mitigate churn factors. Nearly 700 million packets and over 105 thousand RTTs were gathered in total.

3. ROUND-TRIP DELAY

Interactive applications have critical delay requirements. As far as video communication, there is no or little impact below 150 ms one-way end-to-end delay, and serious disturbance above 400 ms [5]. The feasibility and efficiency of utilizing overlay to improve delay performance have already been presented in some literature [6]. In this data set, the average RTT of the SDPs is 219 ms, whereas that of SInPs is 400ms. However, nearly 30% of the SInPs have lower RTT than its corresponding SDP, and the best SInP in RTT between each pair of sender and receiver has an average RTT of as low as 170 ms.

Fig.1 illustrates the cumulative distribution function (CDF) of the RTTs. Under SDP, the majority (81%) of the RTTs are below 300 ms, and 98% are below 800ms (double of the one-way delay demand). Though only 51% of the SInPs satisfy the 300ms bound and 97% satisfy the 800ms bound, the best SInP in delay between each pair of sender and receiver can increase the former to 92% and the latter to 100%. Even the 30 best SInPs in delay between each pair of sender and receiver (about half of the whole SInP set) behave no much difference with the SDPs from the comparison of the CDF curves.

4. PACKET LOSS

4.1 Average Loss Rate

Generally speaking, higher packet losses tend to weaken the effects of error correction scheme in video decoder, thus degrade video quality. Table 2 lists the comparison among different video delivering schemes in terms of average packet loss rate. The result suggests that the packet redundancy in DPM is effective at masking transient loss by avoiding about 70% of the losses in SDP. DPRR does not introduce higher loss, but on the other hand lightens it a little except the bit rate of 128Kps. Maybe it could be explained that sending packets at half speed in individual path will potentially decrease the losses in each path, which was also proved theoretically in [3] by a Gilbert model.

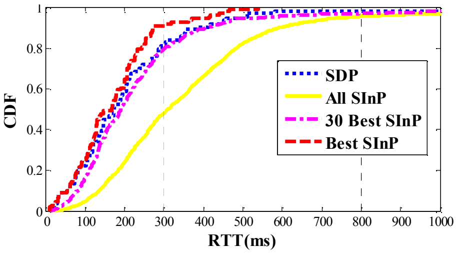

Fig.1. CDFs of RTTs

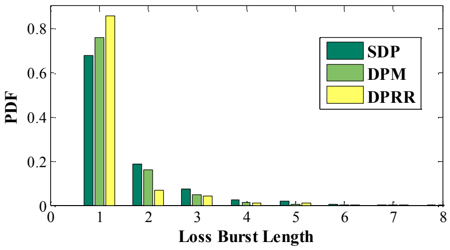

Fig.2. PDF and Loss Burst Length

4.2 Loss Burst Length

A large number of consecutive packet losses not only contributes to significant degradation in video quality, but also diminishes the ability to recover such losses through error correction techniques, such as multiple-description coding (MDC) and forward error correction (FEC) [3]. However, if congestion happens on either path, but not simultaneously on both, it would expect the number of successive lost packets to be smaller in DPRR than in SDP.

During this experiment, the average loss burst length of SDP was 1.72, which fell to 1.30 in DPRR and 1.45 even in DPM. Not strictly, we try to explain the result in DPM as follows: one more consecutive packet loss adds one loss burst length in SDP, while, roughly two more consecutive packet losses adds one loss burst length in DPM, which is "harder" than one more consecutive packet loss, so the average burst length in DPM is shorter than that in SDP. Fig.2 shows the probability density function (PDF) of the loss burst length. Without loss of generality, the figure stops at burst length 8, covering more than 99.5% of the bursts.

5. DELAY JITTER

When packets are transmitted over the Internet, they may experience variable delay, called delay jitter, which is another important parameter that should be taken into account in the support of interactive video. For non-real-time data transfer applications, such as ftp and http, delay jitter has little real impact. By contrast, real-time applications, especially interactive applications, large delay

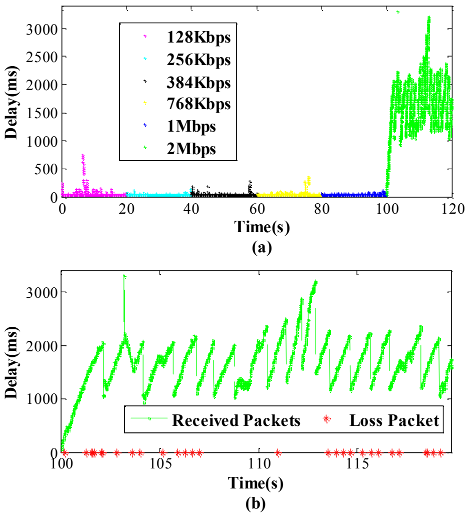

Fig.3. One Way Delay Jitter Time Series of a SDP

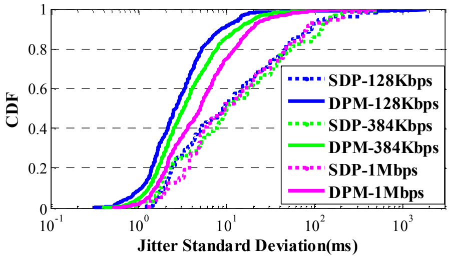

Fig.4. CDF of the Standard Deviation of One Way Delay

variation reduces the chance of delivering packets successfully before their decoding deadlines.

5.1 Over Rate

Fig.3 (a) gives the time serial of one way delay jitter on a SDP during 2 minutes time. When packets transmission rate is below the available bandwidth of this SDP, the end-to-end delay follows a Gamma-like shape with a single-side heavy tail [7], large delay is not frequent. However, once the transmission rate exceeds the available bandwidth, when a packet is significantly delayed, a substantial number of the following packets are delayed as well, creating a "snowball", until the router along the SDP drops a few packets which makes the immediate delays decrease and a new "snowball" cycle begin. The latter phenomenon is defined as over rate in this paper. Fig.3 (b) magnifies the time serial curve with the transmission rate at 2Mbsp in Fig.3 (a) and shows the radical and serrate delay jitter in over rate in detail.

In case of over rate, one can reduce the packet transmission rate at the cost of video quality degradation. However, sending data through multi-path may increase the aggregate bandwidth, as far as the selected SInP bypasses the bottleneck link of SDP**.** Table 3 shows approximately two thirds of the over rate can be avoided by DPRR in our data set. In the other one third over rate cases, bottleneck may be located at access points or just not bypass via the *forwarders* in our test bed.

Table 3. Over Rate SDPs and Settled by DPRRs

Bit Rate	Over Rate	Settled
128Kbps	5	4
256Kbps	2	2
384Kbps	4	4
768Kbps	10	5
1Mbps	6	3
2Mbps	11	7

5.2 Standard Deviation

Under multi-path condition, if not all paths experience the same traffic patterns and congestion, it is expected that at least one path will avoid heavy jitter, as a result, DPM or DPRR combined with MDC or FEC will be helpful in improving video quality. This and next subsection validate this hypothesis by the following two parameter in statistics — standard deviation and correlation coefficient.

Fig.4 suggests that nearly 50% SDPs suffer the standard deviation of delay from tens to hundreds milliseconds, which falls to 10% to 25% in DPM based on the statistics of 109 thousand 20 seconds lasting consecutive packets sequence.

5.3 Correlation Coefficient

As inherent delay gap exists between a pair of SDP and SInP, DPRR doesn't exhibit advantage in term of standard deviation. This subsection introduces correlation coefficient as a measure of the dependency degree between the delay jitters on SDP and SInP. Given two delay serials $\{X_t\}$ and $\{Y\}_t$ on two paths during the same period of time, their correlation coefficient is formulated as followed:

$$Corr[X_t,Y_t]=\frac{E[(X_t-\overline{X})(Y_t-\overline{Y})]}{\sqrt{E[(X_t-\overline{X})^2]}\sqrt{E[(Y_t-\overline{Y})^2]}}=\frac{E(X_tY_t-\overline{XY})}{\sqrt{E[X_t^2-\overline{X}^2]E[Y_t^2-\overline{Y}^2]}} \quad (2)$$

If there is high positive relationship between the two delay serials, $Corr[X_t,Y_t]$ closes up to 1, which indicates the two paths are likely to encounter jitter at the same time. If high negative relationship between the two delay serials, $Corr[X_t,Y_t]$ approaches -1, which indicates whenever one path has a high (low) delay, the other tends to have a low (high) delay. $Corr[X_t,Y_t]$ closes 0 means that there is low linear relationship between the two delay serials.

Fig. 5 depicts the CDF of the correlation coefficient of 1928 pairs of SDP and SInP, which are selected from the total of 5928 pairs in term of the similarity of packet loss rate and the standard deviation of delays. It shows that almost 87% of the pairs have rather low correlation, with correlation coefficient ranging from -0.2 to 0.2. It is expected that the DPRRs formed by such pairs of paths are capable of eliminating the effects of heavy jitter with high probability by some further error erasure schemes.

Table 4. Average PSNR (dB) and Reconstruct Frames

Bit Rate	SDP		All DPM		All DPRR		Selected DPM		Selected DPRR	
	PSNR	Frame	PSNR	Frame	PSNR	Frame	PSNR	Frame	PSNR	Frame
128Kbps	24.8	250	30.1	296	28.7	289	30.9	298	30.6	294
256Kbps	26.0	248	/	/	29.3	285	/	/	31.4	293
384Kbps	26.0	241	31.4	291	29.7	281	32.5	295	32.4	294
768Kbps	26.7	232	/	/	30.9	276	/	/	34.5	293
1Mbps	27.0	232	33.2	282	31.4	272	35.2	2.93	35.6	293
2Mbps	27.7	228	/	/	31.8	270	/	/	36.1	293

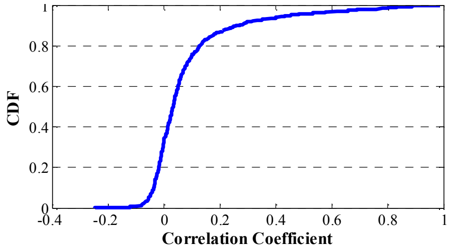

Fig.5. CDF of the Correlation Coefficient of SDP and SInP

6. PSNR

In order to integrate the effects of the above three network parameters from section 3 to 5 and get a general conclusion of multi-path effects, this section simulates interactive video streaming process offline. First, encode a 300 frames Foreman CIF (352x288) sequence at 30 frames per seconds, with groups of pictures (GOP) size of 15 frames by a standard MPEG-4 codec. "Foreman" is a head-and-shoulders type video sequence with medium motion similar to a videoconferencing scenario. Second, packetize the encoded streams in step 1. Third, map the packets in step 2 with the packets sequence in our data set and recombine them as "received" streams, where the delay tolerance is set to 400 ms. Both packet losses and delay is taken into account because large delay jitter will also translate into losses in interactive video. About 318,000 10 seconds lasting video streams are obtained in this step. Fourth, decode the streams in step 3. The above process doesn't add any further error erasure scheme to reserve the effects of multi-path only. Video quality is measured by reconstructed frame numbers and PSNR given by $PSNR = 10\log_{10}\left(\frac{255^2}{MSE}\right)$, where MSE stands for the mean squared error between corresponding pixels in the each frame.

The results summarize in Table 4 show that multi-path approaches are indeed useful on video quality improvement. On average, DPM increases PSNR by 5.3dB to 6.2 dB, and DPPR increases it by 3.3dB to 4.4 dB. After carefully selecting 10 to 20 best SInPs from all the 62 SInPs for each SDPs according to RTT, packet loss rate and delay standard deviation, these two approaches perform similarly at the same bit rate. However, considering the duplication in DPM doubles bandwidth uses, DPRR will be 0.5dB to 2dB better in the condition of same bandwidth utilization.

7. CONCLUSION

This paper presents an empirical study on the benefits that can be obtained through multi-path streaming over best-effort wide-area network. The results indicate that: (1) In general, DPM guarantees reliable performance improvement at the cost of sending redundant packets. (2) DPRR makes full use of the bandwidth resource and tends to perform better than DPM providing elaborately probing and selection. (3) Both of them exhibit significantly better performance than SDP. These results are quite encouraging, and warrant further study on multi-path interactive multimedia system, such as finding competent *forwarder*, and designing more effective error erasure techniques, which are also our future work.

8. REFERENCES

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