An Analytic Comparison of RPS Video Repair

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ABSTRACT

Transmitting high-quality, real-time interactive video over lossy networks is challenging because network data loss can severely degrade video quality. A promising feedback technique for low-latency video repair is Reference Picture Selection (RPS), whereby the encoder selects one of several previous frames as a reference frame for predictive encoding of subsequent frames. RPS operates in two different modes: an optimistic policy that uses negative acknowledgements (NACKs) and a more conservative policy that relies upon positive acknowledgements (ACKs). The choice between RPS NACK and RPS ACK depends on network conditions, such as round-trip time and loss probability, and on the video content, such as low or high motion. This paper derives two analytical models to predict the quality of videos (using Peak Signal to Noise Ration, PSNR) with RPS NACK and RPS ACK. These models are used to study RPS performance under varied network conditions and with different video contents through a series of experiments. Analysis shows that the best choice of ACK or NACK greatly depends upon the round-trip time and packet loss, and somewhat depends upon the video content and Group of Pictures (GOP) size. In particular: 1) RPS ACK performs better than RPS NACK when round-trip times are low; 2) RPS NACK performs better than RPS ACK when the loss rate is low, and RPS ACK performs better than RPS NACK when the loss rate is high; 3) for a given round-trip time, the loss rate where RPS NACK performs worse than RPS ACK is higher for low motion videos than it is for high motion videos; 4) videos with RPS NACK always perform no worse than videos without repair for all GOP sizes; however, 5) below certain GOP sizes, videos without RPS outperform videos with RPS ACK. These insights derived from our models can help determine appropriate choices for RPS NACK and RPS ACK under various scenarios.

Keywords: RPS, Reference Distance, PSNR, H.264

1. INTRODUCTION

Despite improvements in networking and video display technologies, network connections still lose data packets. Lost packets are especially detrimental to streaming video where the dependency between video frames during encoding means that one lost video packet can propagate errors to many subsequent video frames. While video clients can use local concealment to visually cover up transmission loss, the ability to adequately repair video without video server cooperation is limited. For video applications such as video conferencing or interactive, thin-client desktops [1] that have low end-to-end delay requirements, server feedback to request retransmission of lost packets adds too much latency to the video session. Forward error correction (FEC) schemes have been proposed [2] to ameliorate the effects of packet loss, but FEC requires additional channel capacity to stream the video and FEC encoding and decoding can be complicated.

A promising feedback technique for low-latency video repair is Reference Picture Selection (RPS) [3- 5], whereby the encoder uses one of several previous frames as a reference frame for encoding. Broadly, the reference frame can be the previous frame (called *RPS NACK* mode), as is done in typical video encoding, or the reference frame can be several frames older when the encoder waits for the receiver to confirm receipt of the frame (called *RPS ACK* mode). The performance difference between RPS ACK and RPS NACK modes depends upon the latency and loss pattern between the video sender and receiver and also upon the effects of reference distance on the encoded video quality. In particular, videos that do not significantly degrade with high reference distance benefit from the use of RPS ACK while videos that are sensitive to reference distance may choose RPS NACK or another repair technique.

Although numerous studies have detailed the benefits of various repair schemes to video quality [5-7, 11, 12], to the best of our knowledge, there has been no systematic exploration of the impact of video and network conditions on the performance of RPS ACK and RPS NACK. This paper derives analytic models of RPS NACK and RPS ACK to predict the video quality using PSNR. These models are then used to analyze RPS performance under various network conditions and video contents through a series of experiments. A set of high-quality videos with a wide variety of scene

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complexity and motion characteristics are selected. These videos are all encoded using H.264 [8, 9], an increasingly widely deployed compression standard with support for RPS, with a bandwidth constraint and a range of reference distances. Analysis using Peak Signal to Noise Ratio (PSNR) shows that RPS performance is affected by a variety of factors including round-trip time, loss rate, video content and Group of Pictures (GOP) size. In particular, analysis shows that:

- As round-trip times increase, video quality for both RPS ACK and RPS NACK degrades. However, RPS ACK performs better than RPS NACK when round-trip times are low.
- As loss rates increase, the video quality for both RPS ACK and RPS NACK degrades. However, RPS NACK performs better than RPS ACK when the loss rate is low; conversely RPS ACK yields better video quality than RPS NACK when the loss rate is high.
- For a given round-trip time, the loss rate where RPS NACK performs worse than RPS ACK is higher for low motion videos than it is for high motion videos.
- Videos with RPS NACK always perform no worse than videos without RPS for all GOP sizes. However, below certain GOP sizes, videos without RPS outperform videos with RPS ACK.

These insights derived from our models are useful for helping select the repair technique that maximizes video quality, particularly when choosing between RPS ACK and RPS NACK modes.

The rest of this paper is organized as follows: Section 2 describes the analytical models for RPS in detail; Section 3 analyzes the experimental results; and Section 4 draws conclusions and describes possible future research.

2 ANALYTICAL MODEL

This section derives analytical models for RPS ACK and RPS NACK, which aim at capturing the relationship between video quality with ACK or NACK under a variety of network characteristics including packet loss rate, round-trip time and capacity constraints.

The models target H.264 videos since this standard incorporates RPS ACK and RPS NACK, but the models can generally represent any video standard that uses RPS repair. The models assume the independent segment decoding (ISD) mode of H.264 where each GOB is encoded as an individual sub-video independently from other GOBs in the same frame, and the reference picture is selected on a per-GOB basis, i.e., for all macro-blocks within one GOB the same reference picture is used. Since errors inside a GOB do not propagate to other GOBs, the video sequence can be partitioned into independent video sub-sequences. We refer to an independent video sub-sequence as a *reference chain.* Our model assumes that each GOB is carried in a single network packet.

Both models assume reliable transmission of feedback messages since feedback is usually not part of the video syntax and is transmitted via a separate network connection where control information is exchanged [5]. Such a connection may not suffer from congestion as does the forward link, or may use retransmission or other methods to ensure reliable delivery. The models also assume erroneously-decoded GOBs are locally concealed without making any assumptions on specific local concealment techniques. Instead, constant quality for all locally concealed GOBs is assumed. Due to limited space, this paper does not provide the complete details for the analytical models; the reader is referred to [15] for more details.

2.1 Model Parameters

Table 1 provides all the parameters used for our analytical models.

Table 1. Model Parameters

R_F	Encoded frame rate (in frames per second, fps - typical full-motion video frame rates are 25-30 fps)
N_G	GOP size (in frames)
t_{INT}	Time-interval between two frames (in milliseconds, so 4 milliseconds for 25 fps video)
U_r	Average PSNR value for a GOB that is encoded using GOB that is *r* GOBs before it as a reference

U_0	Average PSNR value for an Intra-coded GOB
$U^{'}$	Average PSNR value for a GOB that is repaired using local concealment
t_{RTT}	Round-trip time (in milliseconds)
P	Packet loss probability (fraction)
C	Capacity constraint (in Mbps)
q_n	Probability that *n*-th GOB in reference chain is decoded correctly
$q_{n,r}$	Probability of event that *n*-th GOB in the reference chain is decoded successfully using *r*-th GOB as a reference
Q_n	Expected PSNR value for *n*-th GOB in the reference chain

2.2 Analytical Model for RPS ACK

RPS ACK uses acknowledged frames as references. Since it takes at least one round-trip time for the encoder to receive an ACK for a GOB, the current GOB has to use a GOB which was encoded at least one round-trip time ago as a reference. The age of the GOB selected as a reference GOB grows linearly with the length of the round-trip time. When the encoder uses an older reference GOB, video quality is inherently lowered.

Note that as long as GOB *n* is successfully received, it can be decoded successfully since it can use any previously-acknowledged GOB as a reference. Therefore, the probability of GOB *n* being successfully decoded is:

$$q_n = 1 - p \qquad (2.1)$$

Since the encoder selects the last GOB available without errors at the decoder as a reference, the reference GOB for GOB *n* could be chosen from GOB 1 up to GOB (*n*-*δ*). The probability of decoding GOB *n* correctly using GOB (*n*-*δ*-*i*) as a reference is:

$$(1-p)p^i q_{n-\delta-i}, \qquad 0 \le i \le n-\delta-1, \delta = \left\lceil \frac{t_{RTT}}{t_{INT}} \right\rceil \qquad (2.2)$$

where $q_{n-\delta-i}$ is the probability of GOB (*n*-*δ*-*i*) being successfully decoded, p^i is the probability of *i* consecutive GOBs (preceding the GOB (*n*-*δ*)) having transmission errors and (1-*p*) is the probability of GOB *n* being successfully received.

The use of older reference GOBs for prediction degrades the effectiveness of compression for a GOB. Thus to maintain a constant frame rate and bit rate, the encoder uses a coarser quantization and overall video quality may decrease. To account for video quality degradation when using an older reference GOBs for prediction, U_r denotes the average PSNR for a GOB *n* whose reference GOB is *r* GOBs back in the reference chain.

The expected PSNR for the *n*-th GOB is as follows:

$$Q_n = \begin{cases} (1-p)\sum_{i=0}^{n-\delta-1} U_{\delta+i} p^i q_{n-\delta-i} + p * U^{'}, & n > \delta \\ (1-p)U_0 + p * U^{'}, & n \le \delta \end{cases} \qquad (2.3)$$

where $U^{'}$ denotes the average PSNR for a locally concealed GOB and U_0 the average PSNR for an intra-coded GOB. The values for U_i are obtained from our previous work [13]. Note that the first *δ* GOBs have to be encoded in intra mode since no ACK messages from the decoder will be received prior to encoding.

Since $q_{n-\delta-i}$ is a constant (1-*p*), equation (4.3) can be further simplified as follows:

$$Q_n = \begin{cases} (1-p)^2 \sum_{i=0}^{n-\delta-1} U_{\delta+i} p^i + p * U', & n > \delta \\ (1-p)U_0 + p * U', & n \le \delta \end{cases} \quad (2.4)$$

2.3 Analytical Model for RPS NACK

For RPS NACK mode, one of the GOBs in the previous frame is used as a reference GOB during the error-free transmission. After a transmission error, the decoder sends a NACK for the erroneous GOB with an explicit request to use older, intact GOBs as a reference. Therefore, the encoder may use a GOB in the previous frame or one in an older frame as a reference to encode the current GOB *n* depending upon whether it receives a NACK from the decoder or not. If a NACK is not received from the decoder, the encoder uses a GOB in the previous frame as a reference. The probability of correctly decoding GOB *n* using a GOB in the previous frame as a reference is denoted as $q_{n,1}$, where 1 indicates using the preceding GOB in the reference chain as a reference. If the encoder does receive a NACK, it uses the GOB requested by the decoder as a reference. As in ACK mode, the reference GOB for GOB *n* could be chosen from GOB 1 up to GOB (*n*-*δ*) depending upon which GOB is the last correctly decoded GOB. $q_{n,\delta+i}$ $(0 \le i \le n-\delta-1)$ denotes the probability of decoding GOB *n* correctly using GOB (*n*-*δ*-*i*) as a reference. Since none of the first *δ* GOBs receives a NACK before being encoded, the successful decoding of each subsequent GOB depends upon the success of the preceding GOBs. Therefore, the probability of GOB *n* being successfully decoded is as follows:

$$q_n = \begin{cases} q_{n,1} + \sum_{i=0}^{n-\delta-1} q_{n,\delta+i}, & n > \delta \\ (1-p)^n, & n \le \delta \end{cases} \quad (2.5)$$

The expected PSNR for GOB *n*:

$$Q_n = \begin{cases} U_1 q_{n,1} + \sum_{i=0}^{n-\delta-1} U_{\delta+i} q_{n,\delta+i} + (1-q_n)U', & n > \delta \\ (1-p)^n U_1 + (1-(1-p)^n)U', & 1 < n \le \delta \\ \left(1-p\right) * U_0 + p * \big)U', & n = 1 \end{cases} \quad (2.6)$$

3 ANALYSIS

This section analyzes RPS performance under a variety of network conditions over a range of video contents. The results presented in this section are obtained through a series of experiments using the analytical models described in Section 2. The experiments utilize a set of video clips with a variety of motion content. Each video sequence contains 300 video frames with a frame rate of 25 frames/second (fps). These videos are all encoded using H.264 with a bandwidth constraint and a range of reference distances. The content of these video clips can be roughly categorized into three groups: high motion/scene complexity, medium motion/scene complexity and low motion/scene complexity.

First, the impact of round-trip time on RPS video quality is examined. Figure 1 depicts PSNR versus round-trip time for videos with RPS NACK under varying loss rates. The video clip for this set of experiments is *News*[†] with a GOP size of 22. For all loss rates in Figure 1, as round-trip time increases, average PSNR degrades. However, the degrees of quality degradations are not uniform. Clearly with RPS NACK, video quality under higher packet loss degrades faster versus round-trip time than under lower packet loss. For RPS NACK, each transmission error propagates for a period of one round-trip time so increased packet loss induces more frequent GOB error propagation and video quality degrades quickly.

[†] In this clip, two news reporters are talking with somebody dancing in the background.

Figure 2 depicts PSNR versus round-trip time for videos with RPS ACK under varying loss rates. Similar to the RPS NACK behavior, as round-trip time increases, the average PSNR for videos with RPS ACK degrades for all loss rates. However, RPS ACK video quality degrades slower versus round-trip time under higher packet loss than under lower packet loss. When the packet loss rate is low, the major cause of RPS ACK video quality degradation is increased reference distance (caused by the increased round-trip time); whereas under higher packet loss rates, RPS ACK video quality degradation is attributed more to packet loss than to reference distance (round-trip time).

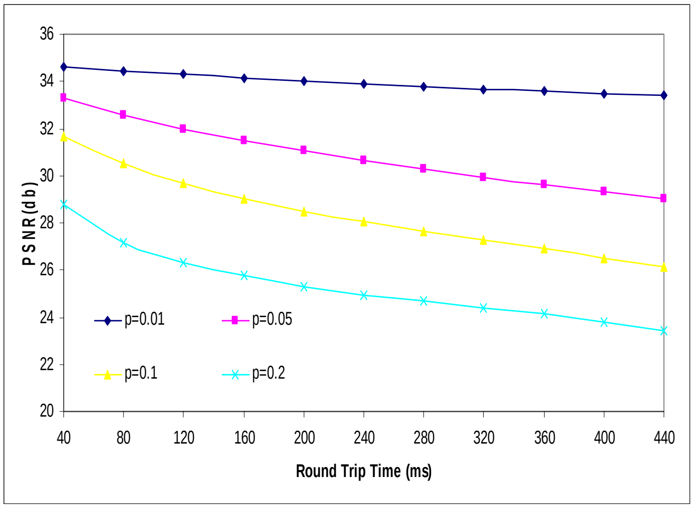

Fig. 1 PSNR vs. RTT with RPS NACK under Different Loss

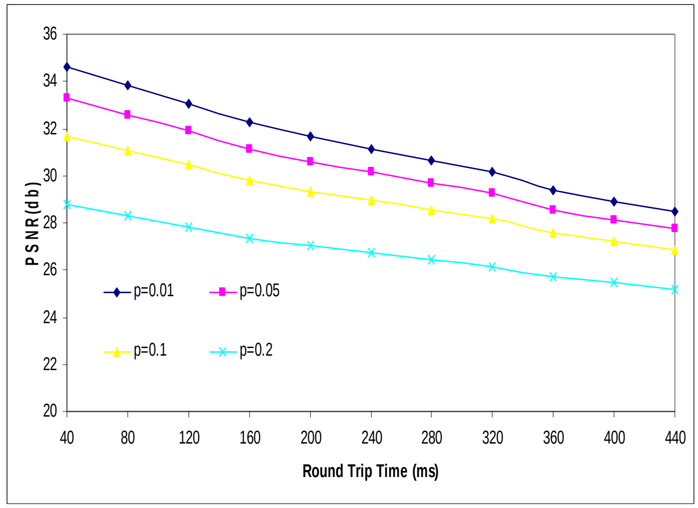

Fig. 2 PSNR vs. RTT with RPS ACK under Different Loss

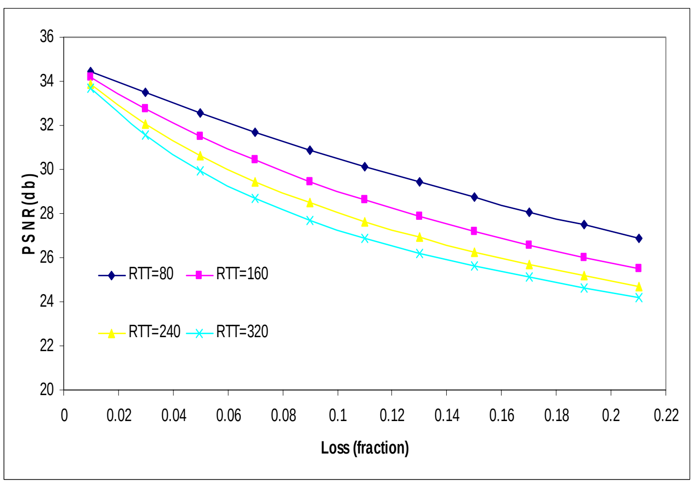

Fig. 3 PSNR vs. RTT with RPS NACK under Different Loss

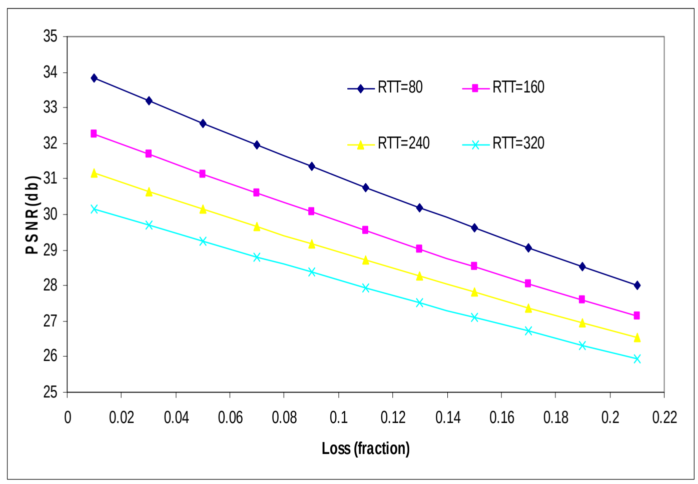

Fig. 4 PSNR vs. RTT with RPS ACK under Different Loss

Changes in RPS video quality as loss probability varies are investigated next. Figure 3 provides PSNR versus loss probability trends for a video encoded with RPS NACK for four distinct round-trip times. As loss probability increases, the average PSNR using RPS NACK degrades for all round-trip times. However, with RPS NACK, video quality under higher round-trip times degrades faster than under lower round-trip times. This is due to the fact that with RPS NACK, larger round-trip times imply longer error propagation periods that causes video quality to degrade. Figure 4 graphs PSNR versus loss probability for a video encoded with RPS ACK for the same four round-trip times. As loss probability increases, like RPS NACK, for RPS ACK the average PSNR degrades for all round-trip times. However, unlike RPS NACK, for RPS ACK the video quality under higher round-trip times degrades slower than under lower round-trip times. Under higher round-trip times, video quality degradation for RPS ACK is attributed more to the round-trip time than to the packet loss, whereas under lower round-trip times, packet loss is the dominant cause of video quality degradation.

Similar trends were observed for five other tested video clips, *Container*, *Silent, Mom-Daughter*, *Foreman* and *Mobile*, representing videos ranging from low to high motion, respectively. Due to space limitations, those results are not presented in this paper.

The prior analysis demonstrates that RPS video quality for both ACK and NACK is affected by round-trip time and packet loss. To make informed decisions about the choice of repair technique, it is useful to know the packet loss range over which RPS NACK performs better than RPS ACK or vise versa, and how the cross-over point changes with round-trip time and video content. Figures 5-7 compare RPS NACK and RPS ACK under different round-trip times by graphing PSNR versus packet loss. All three experiments use the *News* video clip. As shown in Figure 5, with an 80 ms round-trip time, when loss probability is less than 0.092, RPS NACK outperforms RPS ACK and when loss probability is larger than 0.092, RPS NACK performs better than RPS ACK. When round-trip time is increased to 160 ms in Figure 6, the cross-over point is reduced to 0.082. Furthermore, in Figure 7 with a round-trip time of 500 ms, the cross-over point is further reduced to 0.075. This suggests that as round-trip time increases, the video quality with RPS NACK degrades faster than RPS ACK. For RPS NACK, increased round-trip time produces longer GOB error propagation; whereas for RPS ACK, increased round-trip time yields higher GOB reference distances. This suggests that increasing error propagation does more harm to video quality than does increasing reference distance.

How the relationship between crossover point and round-trip time is affected by video content is further investigated. Figure 8 shows crossover point versus round-trip time for six distinct videos. For loss rates above the trend lines, RPS ACK performs better than RPS NACK. For loss rates below the trend lines, RPS NACK performs better than RPS ACK. As round-trip time increases, all the video crossover points are lowered. This suggests that regardless of video content, increasing the error propagation is more harmful to video quality than increasing reference distance. For a fixed round-trip time, the crossover points for low-motion videos are higher than for high-motion videos. This implies that RPS ACK outperforms RPS NACK over a wider range of packet loss rates for high-motion videos than for low-motion videos. This is primarily due to the fact that high-motion videos are less sensitive to the change of reference distance and thus can achieve better video quality with RPS ACK.

Finally, the RPS ACK and NACK models are used to investigate the impact of GOP size on video quality. Figure 9 graphs average PSNR versus GOP size for videos with RPS NACK for four round-trip times and the video with no repair. The loss probability for this experiment is 0.05. Below GOP size of 5, PSNR increases in all cases. After GOP size reaches 5, the PSNR for the video without RPS degrades due to error propagation. With RPS NACK, when round trip times are 80 ms and 160 ms, PSNR increases and becomes asymptotically steady. When round trip times are 240 ms and 320 ms, PSNR first slightly decreases and becomes asymptotically steady. For all GOP sizes, videos with RPS NACK perform no worse than videos without RPS and RPS NACK performs better under lower round-trip times than under higher round-trip times since higher round-trip times introduce longer periods of error propagation.

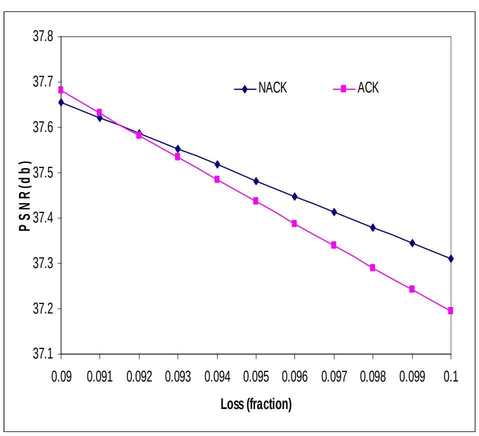

Fig. 5 RPS NACK vs. ACK with RTT= 80ms

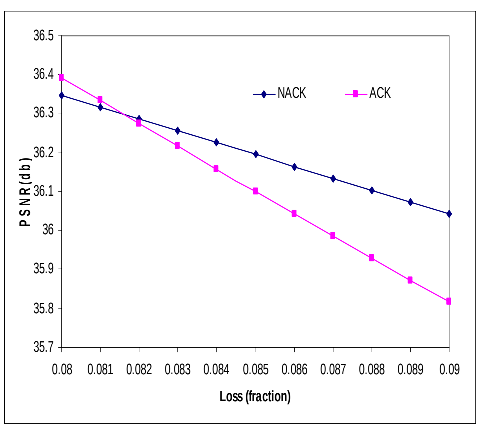

Fig. 6 RPS NACK vs. ACK with RTT= 160ms

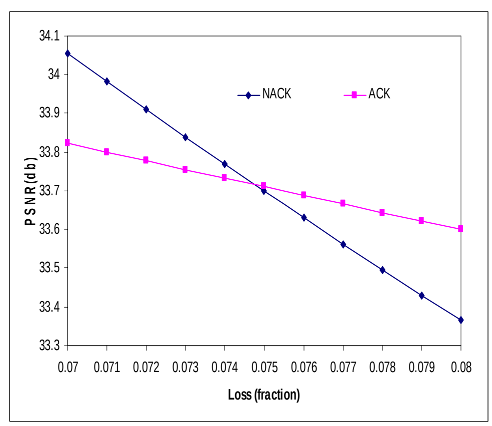

Fig. 7 RPS NACK vs. ACK with RTT= 400ms

Figure 10 depicts average PSNR versus GOP size for videos with RPS ACK under various round-trip times. As GOP size increases, PSNR increases for videos with RPS ACK for all round-trip times shown. Since RPS ACK uses intra coding before any GOBs are acknowledged, the PSNR for the first part of the GOB chain remains constant and increases only after ACKs are received by the encoder.. For all GOP sizes, RPS ACK performs better under lower round-trip times than under higher round-trip times since RPS ACK under higher round-trip times uses older reference GOBs. Notice that below a certain GOP size, video without RPS actually performs better than videos with RPS ACK. For instance, when round-trip time is 80 ms and GOP size is below 8, videos without RPS performs better than videos with RPS ACK. This is because videos without RPS always use the previous GOB as reference and rely on intra coding (the presence of an I block) to stop error propagation. When the GOP size is small, error propagation can be stopped quickly, whereas, RPS ACK always uses older GOBs as reference. Therefore, when the loss probability is low and GOP size is small, videos without RPS outperform videos with RPS ACK.

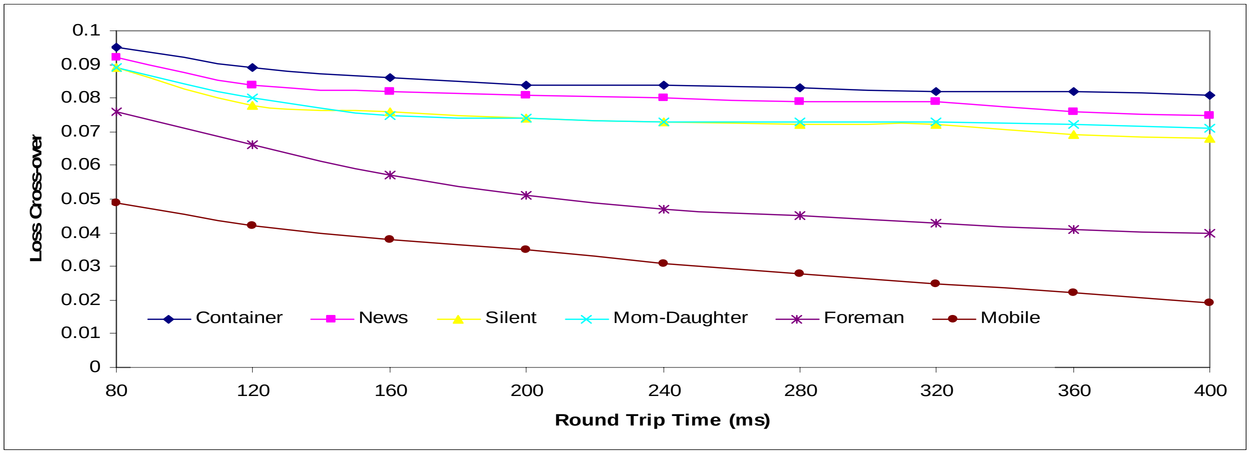

Fig. 8 the Crossover Point for Loss vs. Round-Trip Time for Six Video Clips

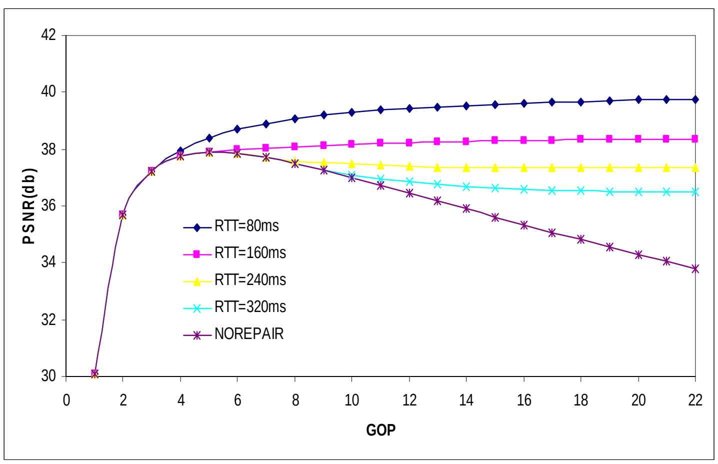

Fig. 9 PSNR vs. GOP with RPS NACK

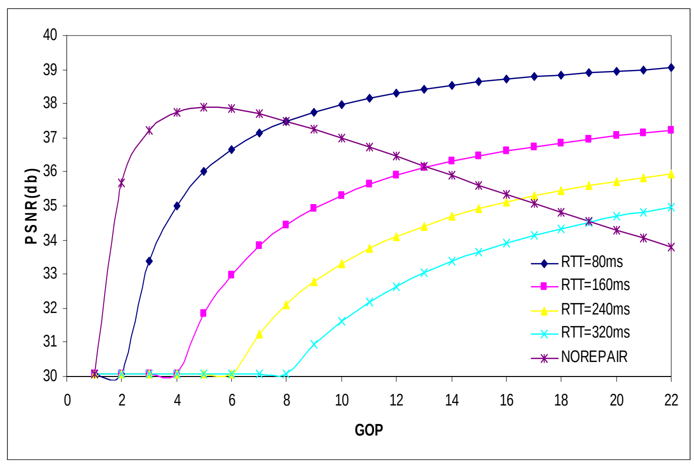

Fig. 10 PSNR vs. GOP with RPS ACK

4 CONCLUSION AND FUTURE WORK

Reference Picture Selection (RPS) is an established video repair technique that allows the encoder to select one of several previous GOBs that have been successfully decoded as a reference GOB for predictive encoding of subsequent GOBs. RPS operates in either ACK or NACK mode. RPS NACK uses the previous GOB as reference during error-free transmission and uses an older GOB as reference when an error occurs. RPS NACK cannot eliminate error propagation since a packet loss results in error propagation for approximately one round-trip time. RPS ACK always uses acknowledged GOBs as reference and thus eliminates error propagation entirely. However, using an older GOB as a reference reduces RPS ACK coding efficiency that produces lower video quality. Therefore, both RPS NACK and RPS ACK have merits and drawbacks. The choice between RPS NACK and RPS ACK depends on network conditions, such as round-trip time loss probability and encoding conditions, such as GOP length and video content. This paper compares RPS NACK and RPS ACK under various network conditions and video content using two analytical models. Analysis using the models shows: RPS ACK is more sensitive to round-trip times whereas RPS NACK is more sensitive to packet loss rates; for a given round-trip time, the loss rate where RPS NACK performs worse than RPS ACK is higher for low motion videos than it is for high motion videos; videos with RPS NACK always perform no worse than videos without RPS for all GOP sizes. However, below certain GOP sizes, videos without RPS outperform videos with RPS ACK.

This study uses PSNR to measure video quality. Future work involves analyzing RPS performance further by utilizing the reportedly more accurate Video Quality Metric (VQM) [14]. Our experiments use a fixed network capacity constraint. Future work could explore the impact of network capacity constraints on the relationship between video quality and reference distance and thus the choices for RPS NACK and RPS ACK.

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