Modeling Path Diversity for Multiple Description Video Communication

John Apostolopoulos, Wai-tian Tan, Susie Wee, Gregory W. Wornell[1]
Client and Media Systems Laboratory
HP Laboratories Palo Alto

HPL-2001-286
November 8th , 2001*

path diversity, multiple description, video compression, streaming

The use of multiple description (MD) video coding and path diversity has been proposed to provide improved performance over lossy packet networks [1]. The goal of this work was to develop models to accurately and quickly predict and compare the distortion of MD video coding and path diversity against conventional single description (SD) video delivered over a single path. In the process, we developed (1) a model for the loss process of a two-path path diversity system, and (2) a distortion model that maps the loss model to MD distortion values. Given these models we present a number of comparisons between MD video coding and path diversity and conventional SD video over a single path. The proposed model for path diversity may also be useful in other applications not related to MD coding. Furthermore, other forms of MD coding may be analyzed using similar models for MD distortion.

* Internal Accession Date Only

Approved for External Publication

[1] Massachusetts Institute of Technology, Cambridge, MA

MODELING PATH DIVERSITY FOR MULTIPLE DESCRIPTION VIDEO COMMUNICATION

John Apostolopoulos, Wai-tian Tan, Susie Wee

Streaming Media Systems Group
Hewlett-Packard Labs, Palo Alto, CA

Gregory W. Wornell

Massachusetts Institute of Technology
Cambridge, MA

ABSTRACT

The use of multiple description (MD) video coding and path diversity has been proposed to provide improved performance over lossy packet networks [1]. The goal of this work was to develop models to accurately and quickly predict and compare the distortion of MD video coding and path diversity against conventional single description (SD) video delivered over a single path. In the process, we developed (1) a model for the loss process of a two-path path diversity system, and (2) a distortion model that maps the loss model to MD distortion values. Given these models we present a number of comparisons between MD video coding and path diversity and conventional SD video over a single path. The proposed model for path diversity may also be useful in other applications not related to MD coding. Furthermore, other forms of MD coding may be analyzed using similar models for MD distortion.

1. INTRODUCTION

Video communication over lossy packet networks such as the Internet is hampered by limited bandwidth and packet loss. Multiple Description Coding (MDC) is one form of compression that may help to overcome this problem. In MDC a signal is coded into a number of separate bitstreams, where the multiple bitstreams are referred to as multiple descriptions (MD). MD coding enables a useful reproduction of the signal when *any* description is received, therefore it is beneficial to increase the probability that at least one description will be received correctly at any point in time.

In [1] it was shown that by combining MD video coding with a path diversity transmission system, where different descriptions are explicitly transmitted through different network paths (as opposed to the default scenarios where they would proceed along a single path), one can improve the effectiveness of MD coding over a packet network by increasing the likelihood that the loss probabilities for each description are independent. A path diversity communication system enables the end-to-end application to effectively see a virtual channel with improved loss characteristics [2, 1]. For example, the application effectively sees an average path behavior, which generally provides better performance than seeing the behavior of any random individual path. Furthermore, the probability that all of the multiple paths are simultaneously congested is much less than the probability that a single path is congested. In addition, path diversity assists certain types of MD coders to recover from losses.

The goal of this work was to develop models to accurately predict distortions when MD video is transmitted using a path diversity system. In the process, we developed (1) a model for the loss process of a two-path path diversity system, and (2) a distortion model that maps the loss model to MD distortion values. With these models we made a number of comparisons between MD video coding and path diversity and conventional single description (SD) video over a single path, and these comparisons are presented in Section 5.

2. MULTIPLE DESCRIPTION VIDEO CODING

This section begins by reviewing MD video coding. We then summarize MD and SD video performance for different types of loss events, and identify the key attributes that describe their performance. These attributes are used in the models developed in the remainder of this paper.

MD coding provides two important properties: (1) each description can be independently decoded to give a usable reproduction of the original signal, and (2) the multiple descriptions contain complementary information so that the quality of the decoded signal improves with the number of descriptions that are correctly received. Note that this first property is in contrast to conventional layered or scalable approaches, which have a base layer that is critically important and if lost render the other bitstreams(s) useless.

A number of MD video coding algorithms have been developed, providing different tradeoffs in compression performance and error resilience [3, 4, 5]. In this paper, we base our work on the MD video coder in [5, 1]. An important property of this MD coder is that it enables the repair of corrupted descriptions using uncorrupted descriptions, therefore providing usable quality even when there are losses in all descriptions, as long as the losses do not simultaneously afflict all descriptions. Additional important properties of this coder include: high compression efficiency (achieving MDC properties with only slightly higher total bit rate than conventional compression schemes), ability to produce descriptions of different or unbalanced bit rate [6], and the codec being a standard compatible enhancement to MPEG-4 Version 2 and H.263 Version 2. Further details in [1, 5].

MD and SD Video Loss Characteristics The Foreman (QCIF) and Bus (CIF) sequences were coded at 30 frames/sec with MD and SD video coding algorithms based on the MPEG-4/H.263-like coder described above. The MD coder coded each sequence into two descriptions (corresponding to the even and odd frames). To make an appropriate comparison, the sequences were coded with MD and SD at the same constant video quality (PSNR) and the same total bitrate (bits/sec). SD coding has a slight compression advantage due to the reduced compression efficiency of MD coding; SD devotes these extra bits to additional intraframe coding which allows it to recover faster from errors. For simplicity, we assume that each packet loss results in the loss of an entire frame. Details of the specific comparisons are given in [1].

Figure 1 illustrates the performance for MD and SD video coding under three types of losses: (1) single loss corresponding to the loss of a single entire frame, (2) two burst losses of 100 ms duration, spaced apart by 2/3 sec, which corresponds to the loss of three frames in two locations spaced apart by 2/3 sec (afflicting both MD streams but at different times), and (3) simultaneous losses in both streams. Distortion is measured in terms of the mean-square error (MSE) per pixel.

We make the following conclusions about SD and MD performance in the face of packet loss. For a single loss (top row), the SD

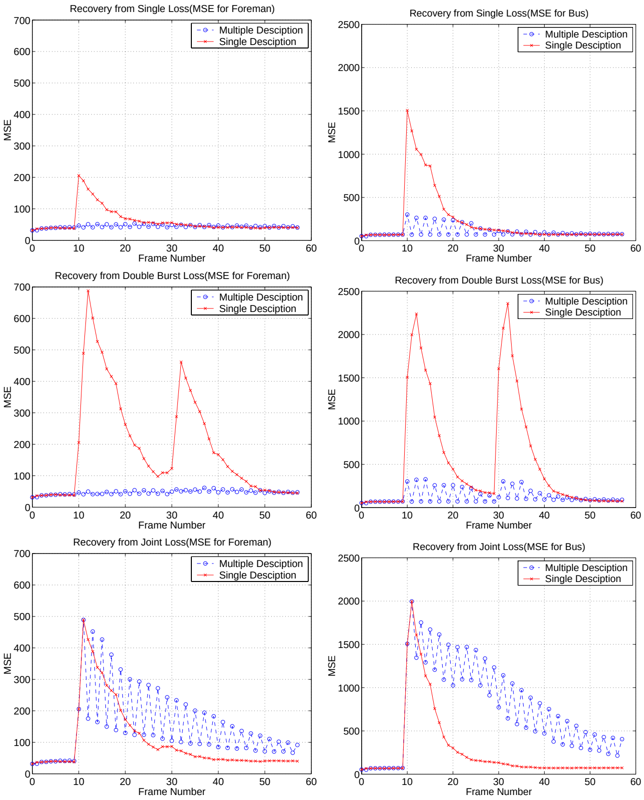

Fig. 1. Recovered SD and MD video quality for Foreman (left) and Bus (right) for single and burst losses in one and both channels.

error is characterized by an initial jump in distortion and a gradual recovery. The MD error is characterized by a very small jump in the corresponding affected even or odd subsequence. The smaller jump in distortion for MD is because the correctly received neighboring frames are used in this form of MD coding to perform state recovery to accurately recover the lost frame. For a burst loss (middle row), the SD error is characterized by a large jump for each consecutive packet loss and a gradual recovery. For a burst loss in one MD path, the MD error is similar to that of a *single* loss; consecutive losses do not result in accumulated distortion because the state recovery at the decoder can recover using correctly received neighboring frames. Therefore, this form of MD coding is largely immune to the duration of loss in one channel. For both SD and MD, losses spaced far enough apart behave as independent losses. For a burst loss (bottom row), the SD error is once again characterized by a large jump for each consecutive error and a gradual recovery. For simultaneous losses in both MD paths, the error is characterized by a jump in distortion for the even and odd subsequences, and each gradually recovers. Note that the MD rate of recovery is slower than that of SD because MD coding uses less intraframe coding (given the same total bit rate constraint).

The effect of each loss event is quantified by a combination of (a) distortion for *individual frames during the loss*, and (b) *sum* of the distortion for the frames *in the following recovery period* (parameters identified by a *"rec"* subscript). We quantify the distortion for SD through 7 distortion parameters: distortion for (1) no loss (D_{noloss}), (2) loss of one frame (D_{drop1}), (3) recovery after loss of one frame (D_{rec1}), (4) loss of a second frame (D_{drop2}), (5) recovery after loss of second frame (D_{rec2}), (6) loss of a third frame (D_{drop3}), (7) recovery after loss of a third frame (D_{rec3}). We assume that the distortion saturates for burst loss length larger than 3. The distortion for MD is quantified with 5 distortion parameters (assuming balanced descriptions): distortion of one description for (1) no loss ($D1_{noloss}$), (2) loss of one frame (affecting only one description) ($D1_{drop}$), (3) recovery after loss ($D1_{rec}$), (4) simultaneous loss of both descriptions ($D12_{drop}$), (5) recovery after simultaneous loss ($D12_{rec}$). Note that it is unnecessary to account for burst length in MD since it is largely immune to the length of the loss as long as the loss afflicts only a single description at any point in time.

3. MODELING SD OVER A SINGLE PATH

In Fig. 1, the total distortion induced by an isolated or burst loss can be approximated by the "spike" and the "area" of its trailing tail. Clearly, for SD the distortion induced by a loss depends strongly on the runlength of the loss. Therefore to accurately capture the effect of burst losses on SD distortion, the distortion model must capture this runlength dependence.

For a single path, the end-to-end loss process is commonly represented by the Gilbert model with transition probabilities $\{p, q\}$, where p is the probability of going from no-loss (0) to loss (1), and q is the probability of going from loss to no-loss [7, 8]. The Gilbert model only models the loss process of a path but not the distortion when video is transmitted over that path. One distortion model for transmitting SD video over a single path is shown in Fig. 2, where the states denote the number of consecutive losses in the immediate past. The distortion for bursts of length longer than 3 is approximated by that of a length 3 burst. Note that the transition probabilities in the distortion model is derived from the parameters of the Gilbert model for the path only, while the distortion associated with state transition is a function of the video source only. Given the distortion model, the average distortion for a particular source and path can be easily computed using the stationary distribution of the states.

Generally, a path consists of the concatenation of N independent links with varying Gilbert parameters. From an end-to-end perspective, we are not interested in the details of which of the N links are bad at any point in time. Instead, our interest is in whether all the links are good, or any of the links are bad. Therefore, the 2^N state of the path can be shown to be equivalent to a two-state Gilbert model with a different set of transition probability $\{p_{total}, q_{total}\}$.

For simulation purposes only in Section 5, we construct single paths of different Gilbert parameters by (1) concatenating different numbers of independent links, each of identical Gilbert parameters $\{p_0, q_0\}$, and (2) varying the Gilbert parameters of the identical links. In such cases, the distortion for any given SD video source over a path of N_{Single} links is a function $D_{SD}(N_{Single}, p_0, q_0)$.

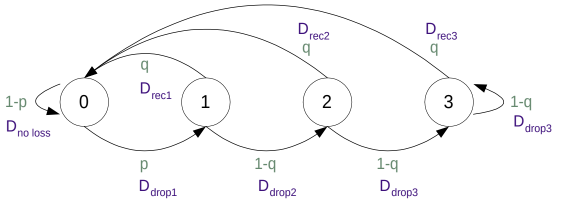

Fig. 2. Model for SD video distortion: The four states identify the burst length, and the transition probabilities and associated distortions are labeled.

4. MODELING MD AND PATH DIVERSITY

In this section, we develop distortion models for the transmission of MD video using a two-path path diversity system. We first describe the representation of the loss process for the two-path path diversity system. Then we describe a distortion model, analogous to that of Fig. 2 for SD, that models the expected MD video distortion over a two-path path diversity system.

4.1. Loss Process for Two-Path Path Diversity

For path diversity with two paths, (e.g., MD with two descriptions each sent over a separate path), there will be a number of joint links that are traversed by both paths, disjoint links that are traversed by path-1 only, and disjoint links that are traversed by path-2 only. We make the simplifying assumption that different links are independent and with loss process given by Gilbert model. Since concatenation of links with independent Gilbert models can be expressed as an equivalent link with Gilbert model, it can be shown that the loss process for the two paths can be summarized by three sets of Gilbert model parameters, corresponding to three subpaths: (1) disjoint links along path-1, (2) joint links along path-1 and path-2, and (3) disjoint links along path-2. Therefore, we do not distinguish based on the specific topology, and instead summarize a two-path path diversity system through three subpaths which explicitly describes either the joint or disjoint portions of each path. While this system may be modeled with an 8-state model, the Cartesian product of the three two-state Gilbert sub-paths, it is important to distinguish the losses that afflict each description in the joint subpath and the dependencies between these losses. For example, the two descriptions may correspond to the even and odd packets, respectively, flowing through the joint subpath, and a burst loss in this subpath would produce dependent losses in both streams. Therefore, we require a 4-state model for the joint subpath, and this leads to a 16-state model for the two-path path diversity system. In addition, the packet rate (packets/sec) for each link must be appropriately accounted for. For example, the appropriate Gilbert parameters vary with packet rate, and the packet rate for each joint link is twice that of each disjoint link.

In summary, a two-path path diversity system can be modeled with a 16-state model and a corresponding 16 × 16 state transition matrix that expresses the transition probabilities from one time instant to the next.

4.2. Distortion Model for MD and Path Diversity

Unlike SD video, we can see from Fig. 1 that for MD video, distortion depends critically on whether loss afflicts both descriptions at the same time, rather than the burst loss length on any single description. Therefore, an appropriate model that captures the distortion behavior of an MD source is the 4-state model in Fig. 3, which expresses at each point in time whether both descriptions are correctly received (state 00), one description is correctly received and one description is afflicted by losses (states 01 and 10) and both descriptions are simultaneously afflicted by losses (state 11). In the case of MD video and two-path path diversity, the transition probabilities of the four states is a function of the transition probabilities of the 16-state loss model described in Section 4.1. Each of the 16 possible transitions corresponds to a different loss event and a different distortion in the reconstructed video. As an example, for this type of MD coding, if we are in state 01 and the next pair of packets is $\{$*lost,received*$\}$, the transition is to state 11 (instead of state 10).

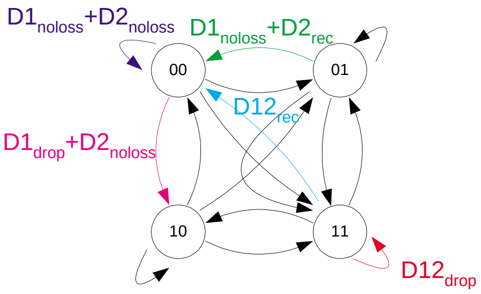

Fig. 3. Model for MD video distortion: The four states identify at each instant in time whether any of the two descriptions are currently afflicted by losses. Each of the 16 different transition arcs corresponds to a different distortion (only 5 are labeled).

The expected MD distortion is computed based on the 4-state model (Figure 3) where the distortion for each transition is quantified by a different combination of the 5 MD distortion parameters. Specifically, the total expected distortion is given by the sum of the products of the steady state probability for each state times the transition probability out of that state times the distortion that results from that transition. This is analogous to the computation of distortion for SD video over a single path using Fig. 2.

For simulation purposes only in Section 5, where each link is assumed to be independent and of Gilbert parameters $\{p_0, q_0\}$, the MD distortion is given by $D_{MD}(N_{Disjoint\text{-}1}, N_{Joint}, N_{Disjoint\text{-}2}, p_0, q_0)$.

Model Validation To validate the accuracy of the proposed path diversity loss model, we compared the distortions obtained by two methods: (1) the proposed analytical model using Gilbert model parameters, (2) simulation traces using the same model parameters. Both cases used the MD and SD distortion parameters of Section 2. In 500 combinations of different path diversities and Gilbert parameters (10^6 packets each) the worst case difference was about 2 % for MD and path diversity and about 1.5 % for SD over a single path.

5. EXAMINING MD VS SD PERFORMANCE

This section examines MD versus SD performance for different path diversity settings and loss characteristics. We assume two MD streams sent over two paths, and the path diversity is expressed by the triplet $\{N_{Disjoint\text{-}1}, N_{Joint}, N_{Disjoint\text{-}2}\}$. The SD path is chosen as the shorter of the two MD paths, $N_{Single} = N_{Joint} + min(N_{Disjoint\text{-}1}, N_{Disjoint\text{-}2})$. Specifically we examine four different situations, and in each case the results for “Foreman” and “Bus” sequences are plotted on the right and left, respectively.

Fixed path lengths and fixed end-to-end loss rate, varying fraction of joint versus disjoint links. Figure 4 shows MD and SD performance when the two paths are of equal length and symmetric ($N_{Disjoint\text{-}1} = N_{Disjoint\text{-}2}$) and we vary the fraction of the total number of links that are joint and disjoint. Specifically, the total length of each path is 8 links, and the number of joint links is varied from 0 to 8 and the number of disjoint links therefore varies from 8 to 0. We assume $\{p_0, q_0\} = \{.0054, .83\}$ for each link, which corresponds to 5 % end-to-end average packet loss for 8 links, and average burst length of 1.25 packets which corresponds to the longest (for 30 msec sampling) that we are aware of in the literature [7, 8].

Different fixed path diversities, vary end-to-end loss rate. Figures 5 shows MD vs SD performance for three different degrees of path diversity as we vary the average packet loss rate per link from 0 to 5 %, and $q_0 = .8$. The three topologies examined are: (1) completely disjoint, topology of {1,0,1}, (2) half disjoint and half joint,

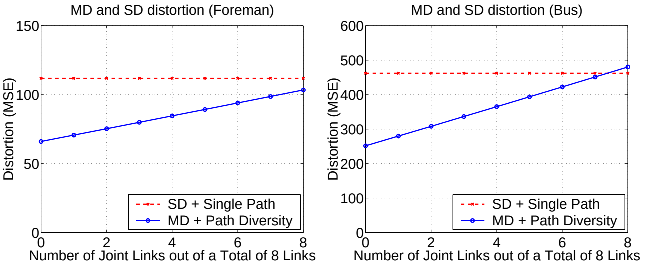

Fig. 4. MD versus SD distortion for equal and symmetric paths, as we vary the number of joint links given that the total number of links is 8. MD provides less distortion than SD for all cases of Foreman (right) and almost all cases for Bus (left) except where the paths are completely joint.

topology of {1,1,1}, and (3) completely joint, topology of {0,1,0}. These topologies examine the spectrum of balanced path diversity cases that range from maximally disjoint, to half of each path being disjoint and half being joint (shared), to maximally joint.

Unbalanced Paths Figure 6 illustrates the performance when the two path are unbalanced with path diversity of {2,1,1}. In this case, MD1 and MD2 have path lengths of 3 and 2, respectively, while SD has a length of 2.

Perfect diversity (independent losses) Figure 7 plots the performance when the loss probability for each packet is independent (both between streams and within each stream – a Bernoulli process), which may be loosely referred to as perfect diversity. This can be achieved by combining path diversity with an appropriate amount of time diversity (via interleaving). This upper bound on performance is identified from our models by setting $q_0 = 1 - p_0$ for the Gilbert parameters.

6. SUMMARY

This paper proposed models for accurately and quickly predicting the distortion of MD video coding and path diversity. Using the models we show that MD and path diversity can provide reduced distortion compared to conventional SD video over a single path for a variety of settings which exhibit path diversity. The proposed loss model for path diversity may also be useful in other applications not related to MD coding. Similarly, other forms of MD coding may be analyzed using a similar model for MD distortion.

7. REFERENCES

[1] J.G. Apostolopoulos, "Reliable video communication over lossy packet networks using multiple state encoding and path diversity," *Visual Communications and Image Processing (VCIP)*, January 2001.

[2] N.F. Maxemchuk, *Dispersity Routing in Store and Forward Networks*, Ph.D. thesis, University of Pennsylvania, May 1975.

[3] V. Vaishampayan and S. John, "Interframe balanced-multiple-description video compression," *ICIP*, Oct. 1999.

[4] A.R. Reibman, H. Jafarkhani, Y. Wang, M.T. Orchard, and R. Puri, "Multiple description coding for video using motion compensated prediction," *IEEE Inter. Conf. Image Processing*, October 1999.

[5] J.G. Apostolopoulos, "Error-resilient video compression via multiple state streams," *Proc. International Workshop on Very Low Bitrate Video Coding (VLBV'99)*, pp. 168–171, October 1999.

[6] J.G. Apostolopoulos and S.J. Wee, "Unbalanced multiple description video communication using path diversity," *ICIP*, October 2001.

[7] M. Yajnik, S. Moon, J. Kurose, and D. Towsley, "Measurement and modelling of the temporal dependence in packet loss," in *INFOCOM*, 1999.

[8] J. Wenyu and H. Schulzrinne, "Modeling of packet loss and delay and their effects on real-time multimedia service quality," *NOSSDAV*, 2000.

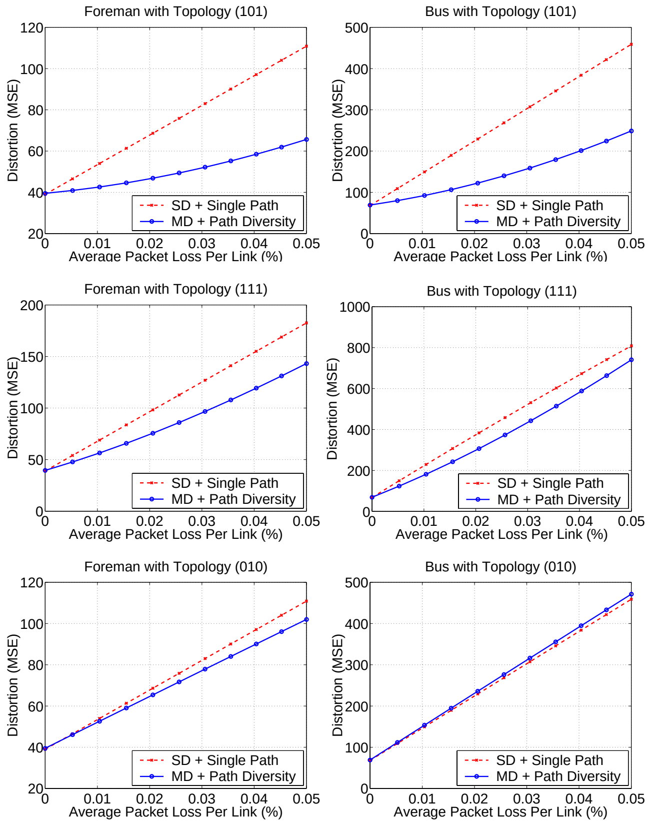

Fig. 5. MD vs SD distortion for three different degrees of path diversity: (top) completely disjoint {1,0,1}, (middle) half disjoint and half joint {1,1,1}, and (bottom) completely joint {0,1,0}.

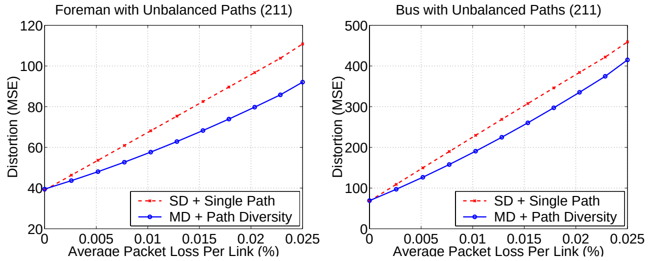

Fig. 6. MD vs SD performance for unbalanced path diversity of {2,1,1}, where MD path lengths are 3 and 2, while for SD it is 2.

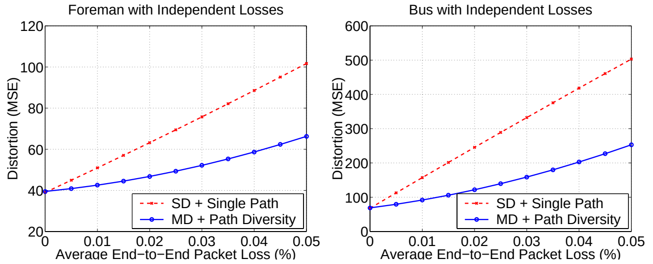

Fig. 7. MD vs SD performance when each has perfect diversity – each packet has independent loss probability (Bernoulli process).