Reliable Video

Multiple Description Video Coding & Path Diversity, and Streaming Media Content Delivery Networks

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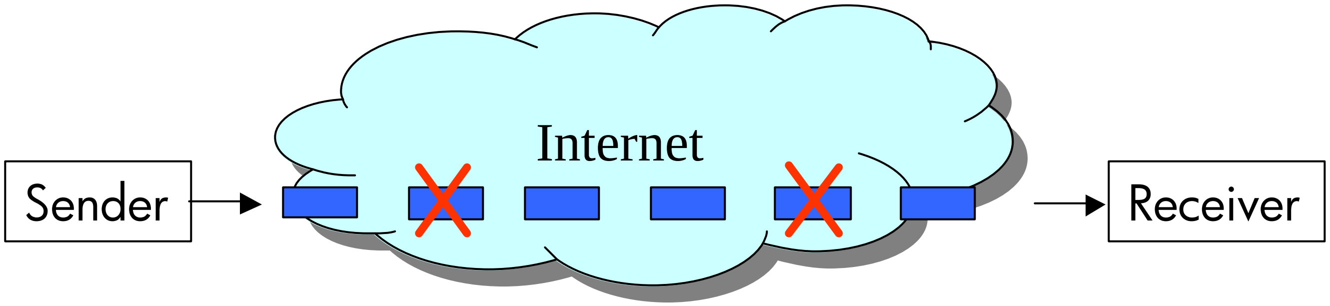
Motivation



Goal: Reliable video communications over lossy packet networks

Desired properties that motivated this work:

- High bandwidth efficiency
- Robustness to losses
- No required feedback channel
- Low delay (e.g. interactive applications)

Design depends heavily on the specific application

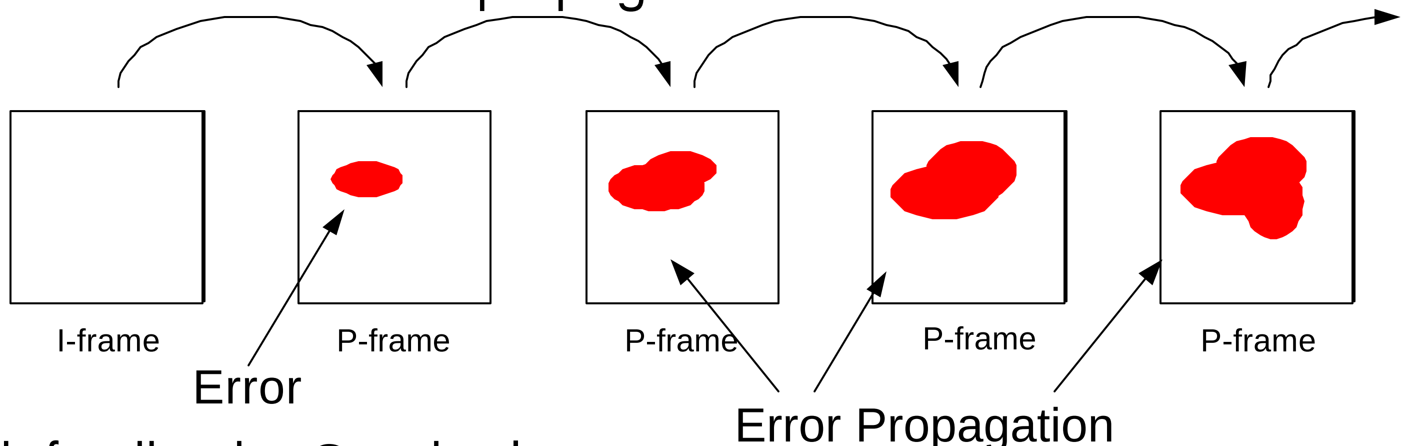
Outline

Goal: Reliable video communications over lossy packet networks

- Techniques
  - Multiple Description (MD) Video Coding
  - MD Coding and Path Diversity
- Modeling and performance evaluation
  - MD Coding & Path Diversity Performance
- Application to real-world system design
  - Multiple Description Streaming Media Content Delivery Network (MD-CDN)

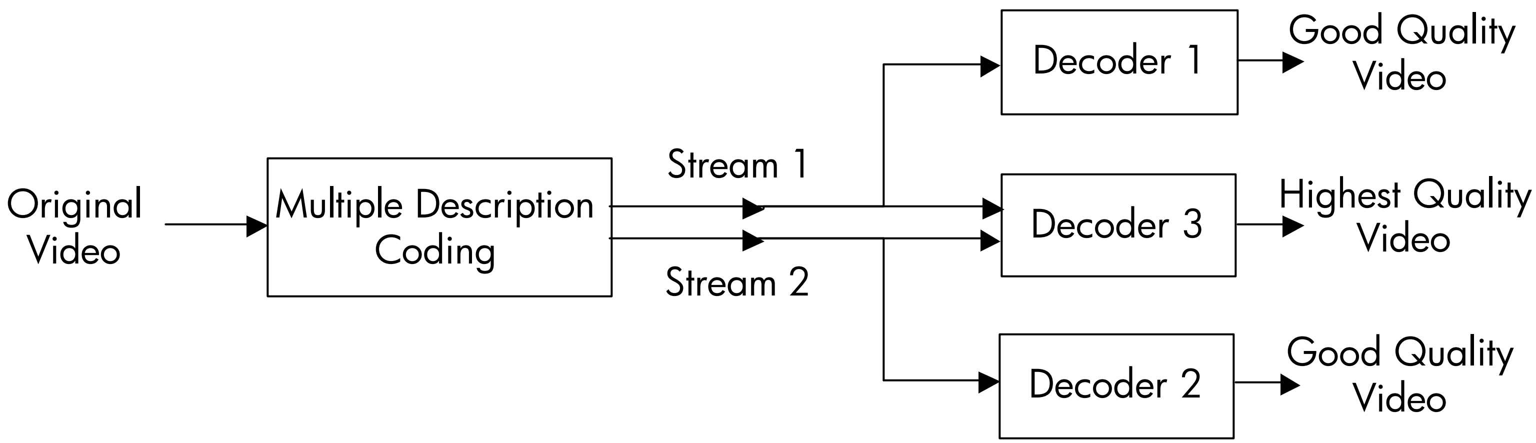
Background

- Problems:
  - Limited bandwidth → Requires high compression, MC-prediction
  - Packet loss → Error propagation



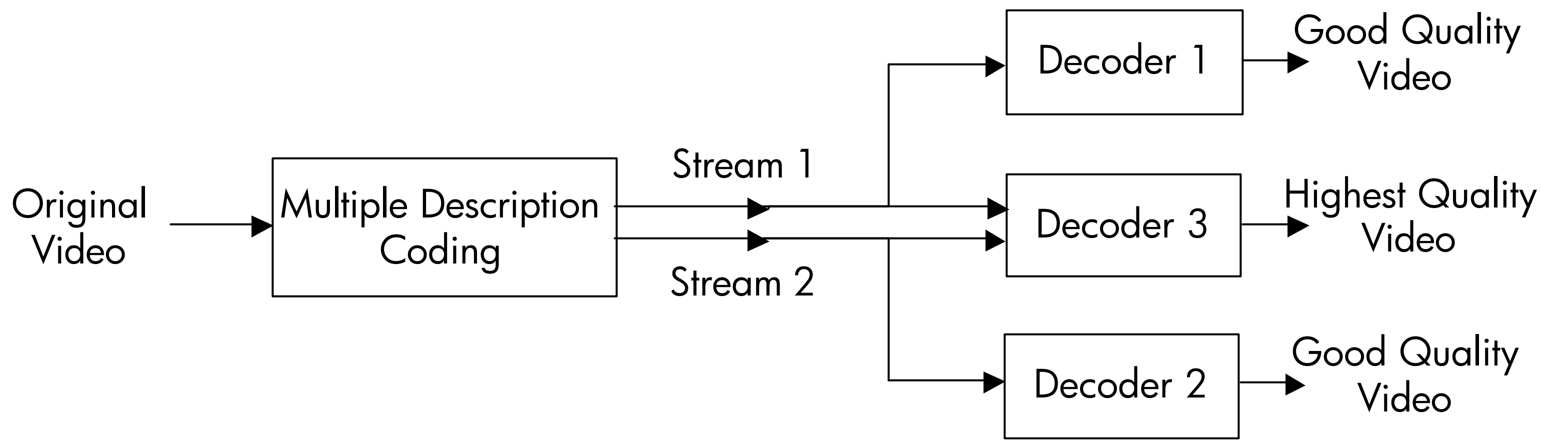
- With feedback: Good solutions exist
  [Fukunaga, Nakai, Inoue; Steinbach, Färber, Girod; Girod, Färber]
- Without feedback: Difficult problem!
  - Strategic intra coding [Hinds, Pappas, Lim; Stuhlmüller, Färber, Link, Girod]
  - Scalable approaches [Tan, Zakhor; MPEG-4 FGS]
  - Many others…
  - Multiple description approaches

Multiple Description Video Coding



- Multiple description (MD) video coding:
  - Code video into a number of descriptions, each of *roughly equal importance*
- Properties of an MD coder:
  - Receiving *either bitstream* leads to good quality video
  - Receiving *both bitstreams* leads to highest quality video

Multiple Description Video Coding (cont.)



- MD video coding approaches:
  - Predictive MD quantizer [Vaishampayan, John]
  - MD transform coding [Reibman, Jafarkhani, Wang, Orchard, Puri]
  - Multiple states and state recovery [Apostolopoulos]
  - FEC-based MD [Puri, Lee, Ramchandran, Bharghavan]

"Error-Resilient Video Compression Via Multiple State Streams", J. Apostolopoulos, VLBV 1999, enhancements at ICIP 2000.

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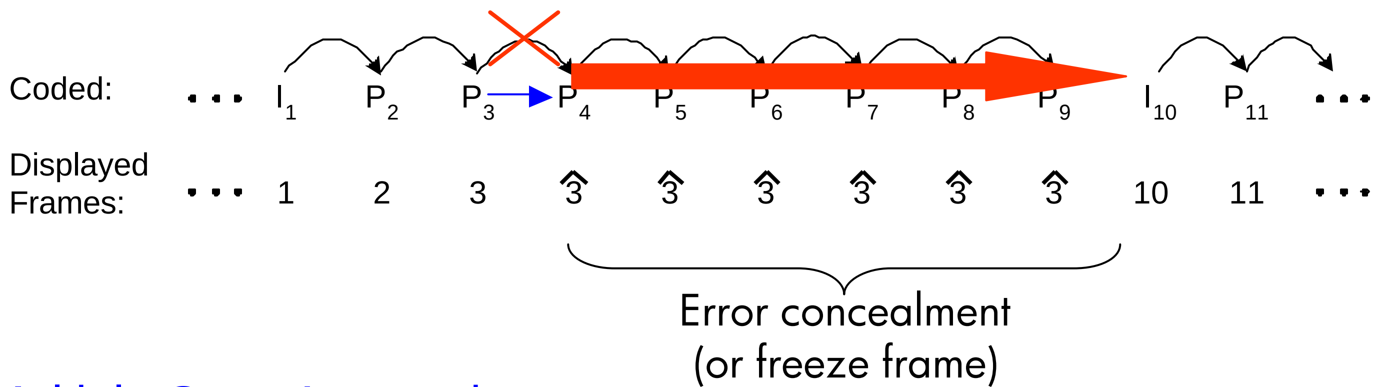
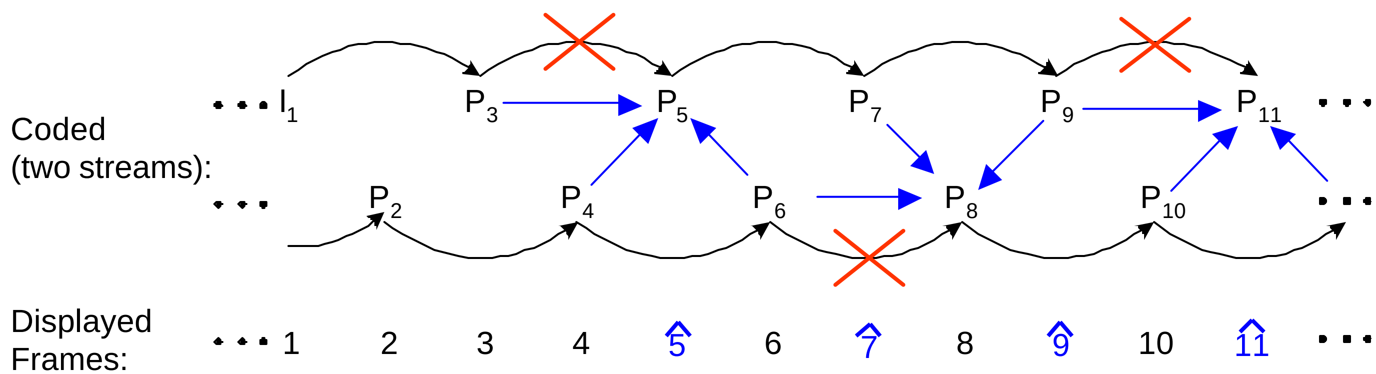
Conventional Single Description (SD) versus Multiple-State Approach

Conventional Single Description (SD) Approach



Extra bits for intra coding

Multiple-State Approach



Extra bits for MD property

Can recover from losses on <u>both descriptions</u>
(as long as both descriptions are <u>not simultaneously lost</u>)

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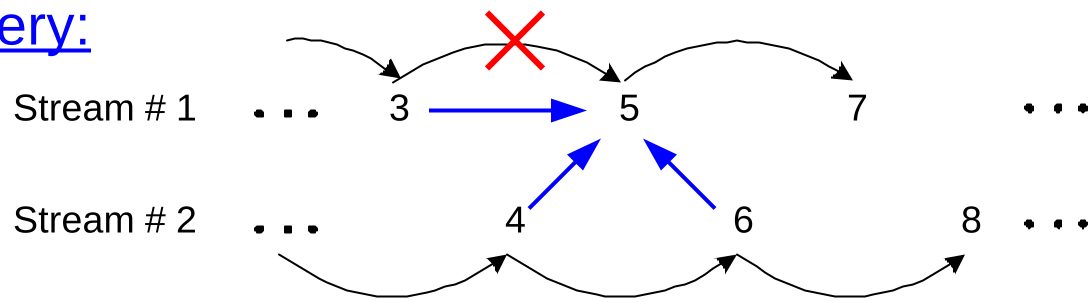
State Recovery (Error Recovery) at Decoder

State Recovery:



- *Novelty: Improved recovery from errors*
  - Other approaches only have access to *previous frames*
  - Proposed approach has access to *previous and future frames*
  - → *Bi-direction information* significantly improves recovery
- State recovery is similar to MC-interpolation [VLBV 1999, ICIP 2000]
  - MC-interpolation in this work:
    - Phase-correlation motion estimation
    - Dense motion field
    - Identify occlusions (covered & uncovered pixels)
    - Estimate lost frame as appropriate MC-combination of surrounding frames

Experimental Results

SD with extra intra coding (e.g. MPEG-4)

Multiple Description

- Same total bit rate and quality for SD and MD – differ only in error resilience properties
- Burst loss (congestion of 100 ms duration, 3 frames lost)
- Standard-compatible enhancement to MPEG-4 V2, H.263 V2, H.26L

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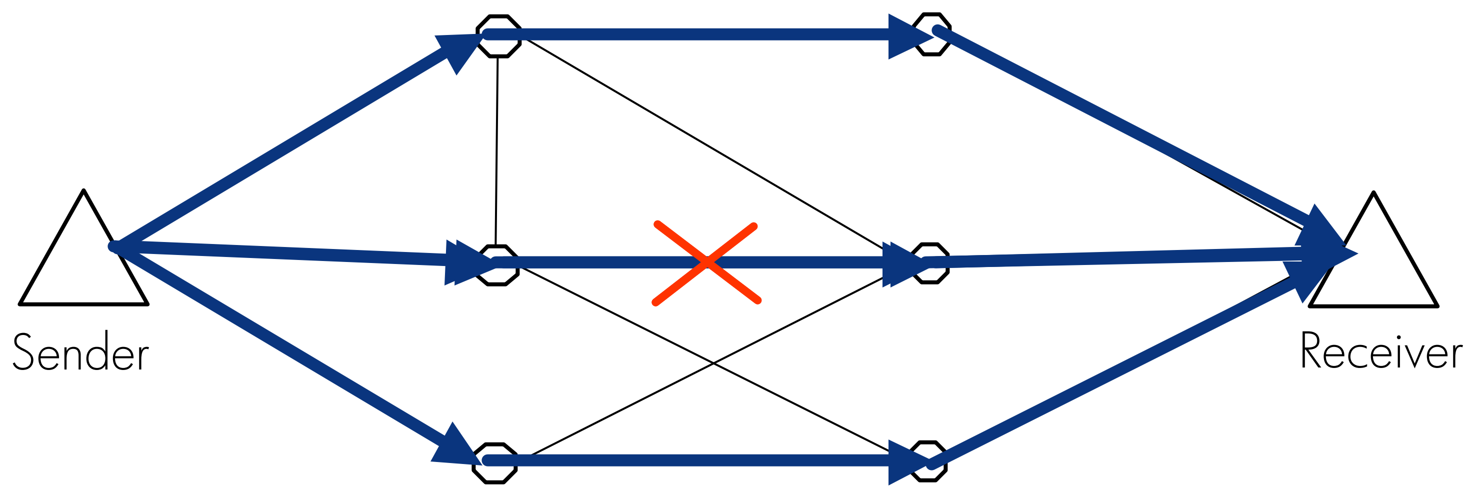
Path Diversity

- Major problem communicating over the Internet:
  - Packet loss with unpredictable, time-varying characteristics
- Situation:
  - While one node or path is congested, others are fine
  - Difficult to identify "best path" at any point in time
- Idea: Use a number of paths at the same time → Diversity [Apostolopoulos, Wornell]
  - Diversity has been used in wireless for many years
  - Great variability in the Internet [Paxson] → Analogous to the motivation for wireless
  - Limited prior work [Maxemchuk; Ayanoglu, I, Gitlin, Mazo; Banerjea]

Path Diversity: Basic Idea



Congestion on single link does not severely affect video communication

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Path Diversity (cont.)

- Recent work adds justification for path diversity over a packet network [Savage, Collins, Hoffman]:
  - Compared performance between default path and alternative path between two hosts on the Internet

    "in 30-80% of the cases, there is an alternative path with significantly superior quality"

- Approaches for achieving path diversity:
  1. Source Routing
  2. Relay Infrastructure (Overlay network of relays)
  3. Content delivery network (later in talk)

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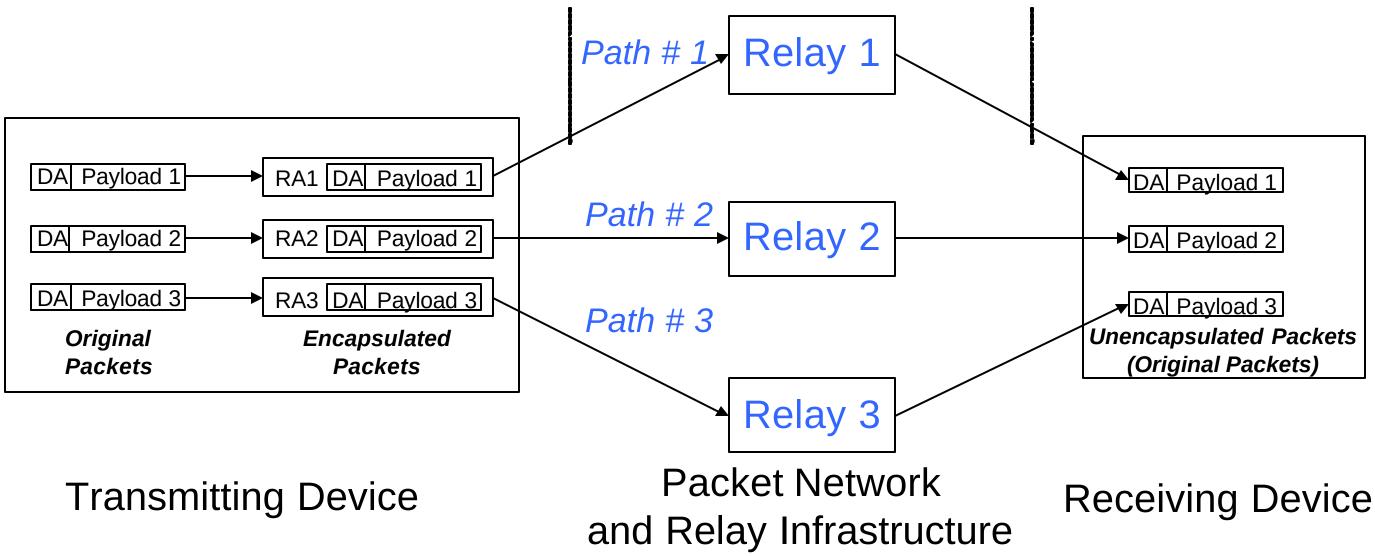
Path Diversity via Relay Infrastructure



- Relay Infrastructure for providing path diversity:
  - Send each MD stream through a different relay placed at a strategic node in the network
- Application-specific overlay network on top of the Internet
  - Provides a service of improved reliability while leveraging the infrastructure of the Internet

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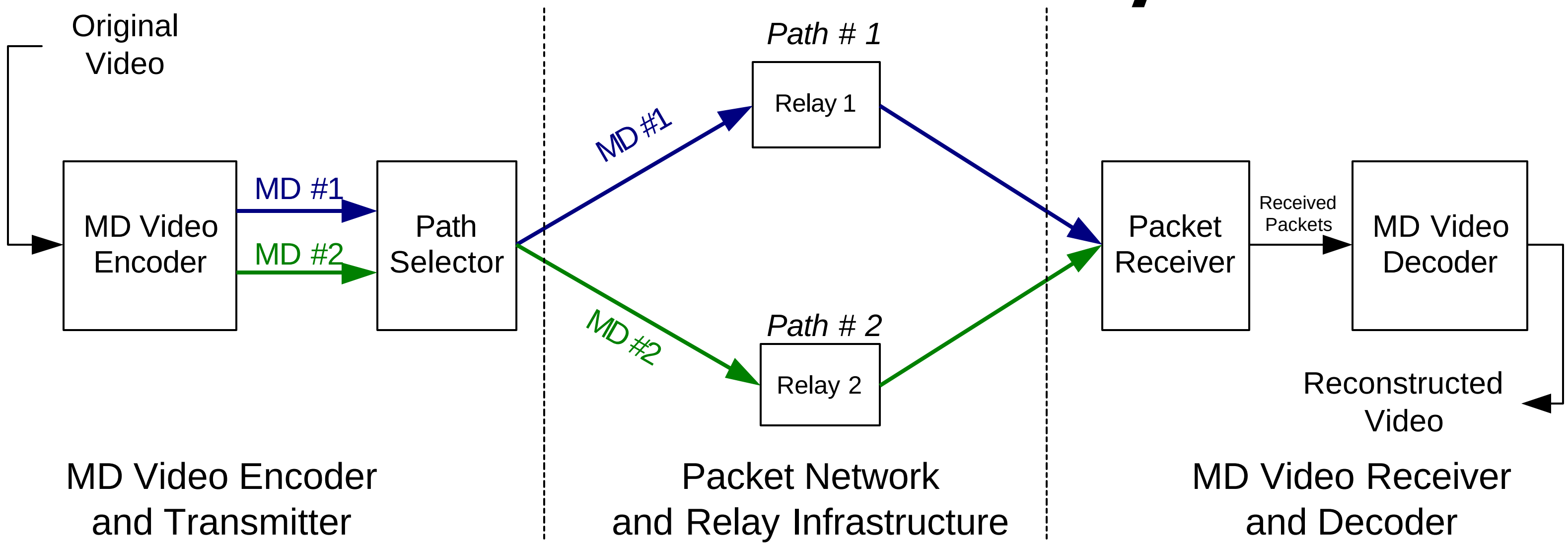
Proposed System Architecture: MD Video and Path Diversity



Proposed System:

- Multiple description video coding
- Path diversity transmission system
- State recovery within MD decoder
  - Enables decoder to recover from losses (as long as both descriptions are not simultaneously lost)

"Reliable Video Communication over Lossy Packet Networks using Multiple State Encoding and Path Diversity", J.G. Apostolopoulos, VCIP, January 2001.

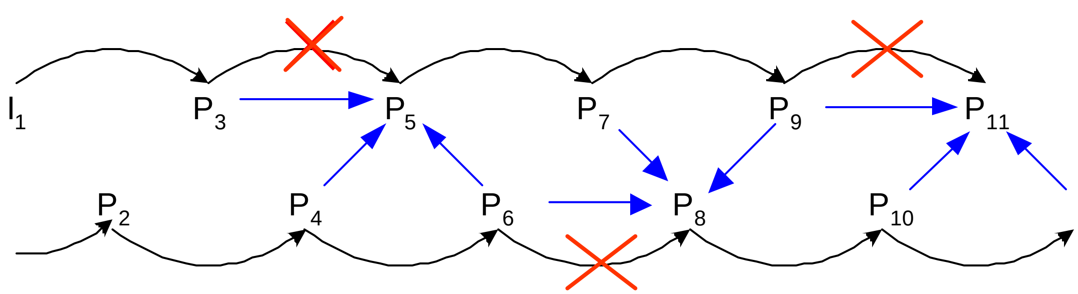
Experimental Setup

- SD vs MD comparison:
  - Same total bitrate, and same quality (for no loss)
  - Differ in error resilience:
    - SD uses Intra coding
    - MD has MD property & state recovery
- Examine four different loss events:
  1. Single packet loss (loss of 1 frame)
  2. Burst loss of 100 ms (loss of 3 frames)
  3. Double burst losses of 100 ms, spaced apart by 2/3 sec (loss of 3 frames at two locations)
  4. Simultaneous losses on both descriptions

MD better (1–3)

SD better (4)

Multiple-State Approach



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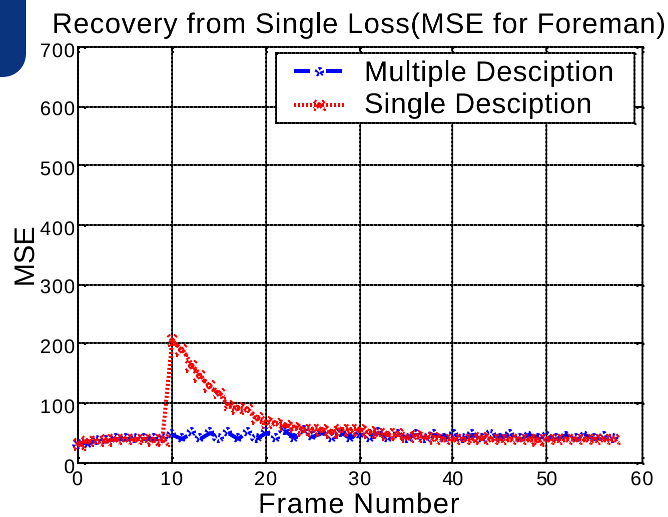
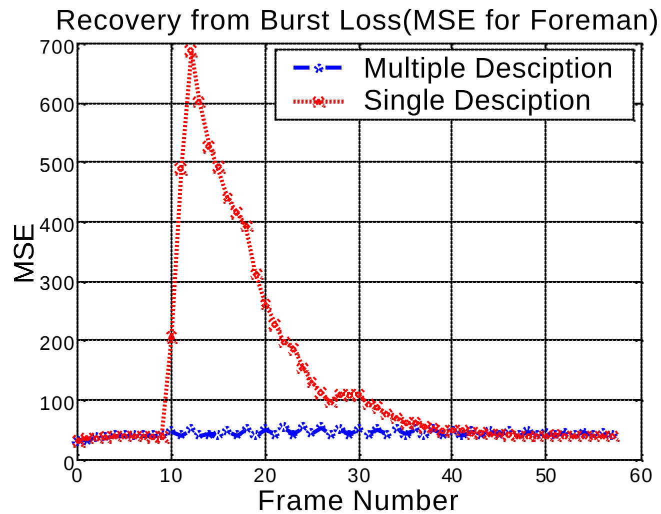
Experimental Results: Foreman Sequence

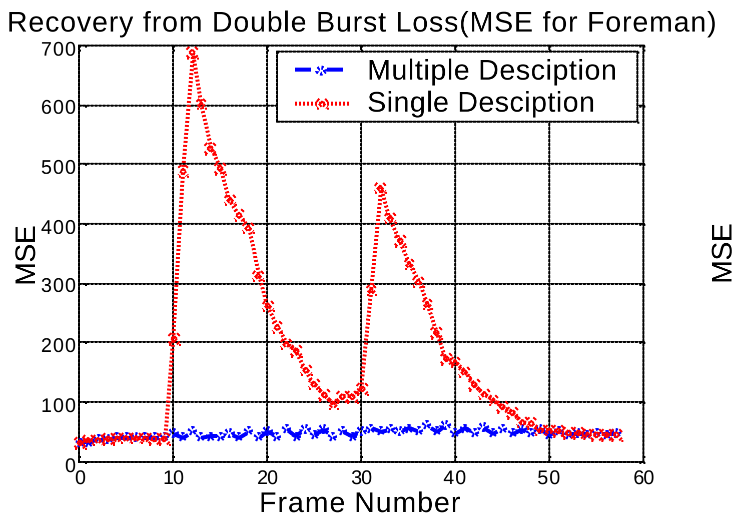
Single Loss



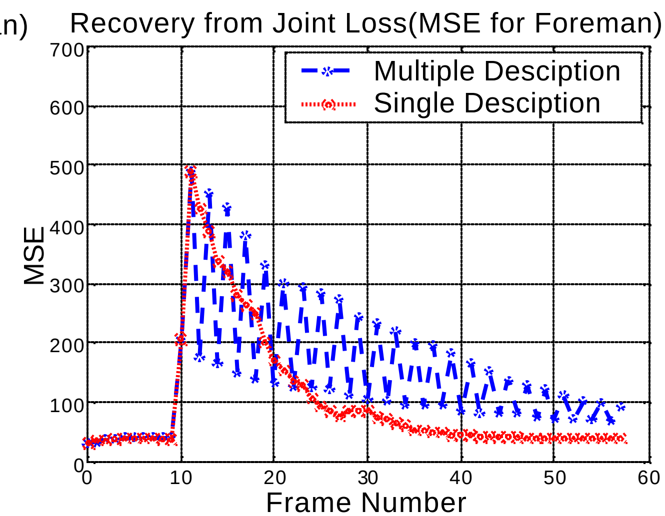
Burst Loss



Double burst loss



Simultaneous losses



- SD significantly more vulnerable to losses and length of loss
- MD largely immune to the duration of the loss, as long as both descriptions are not simultaneously corrupted

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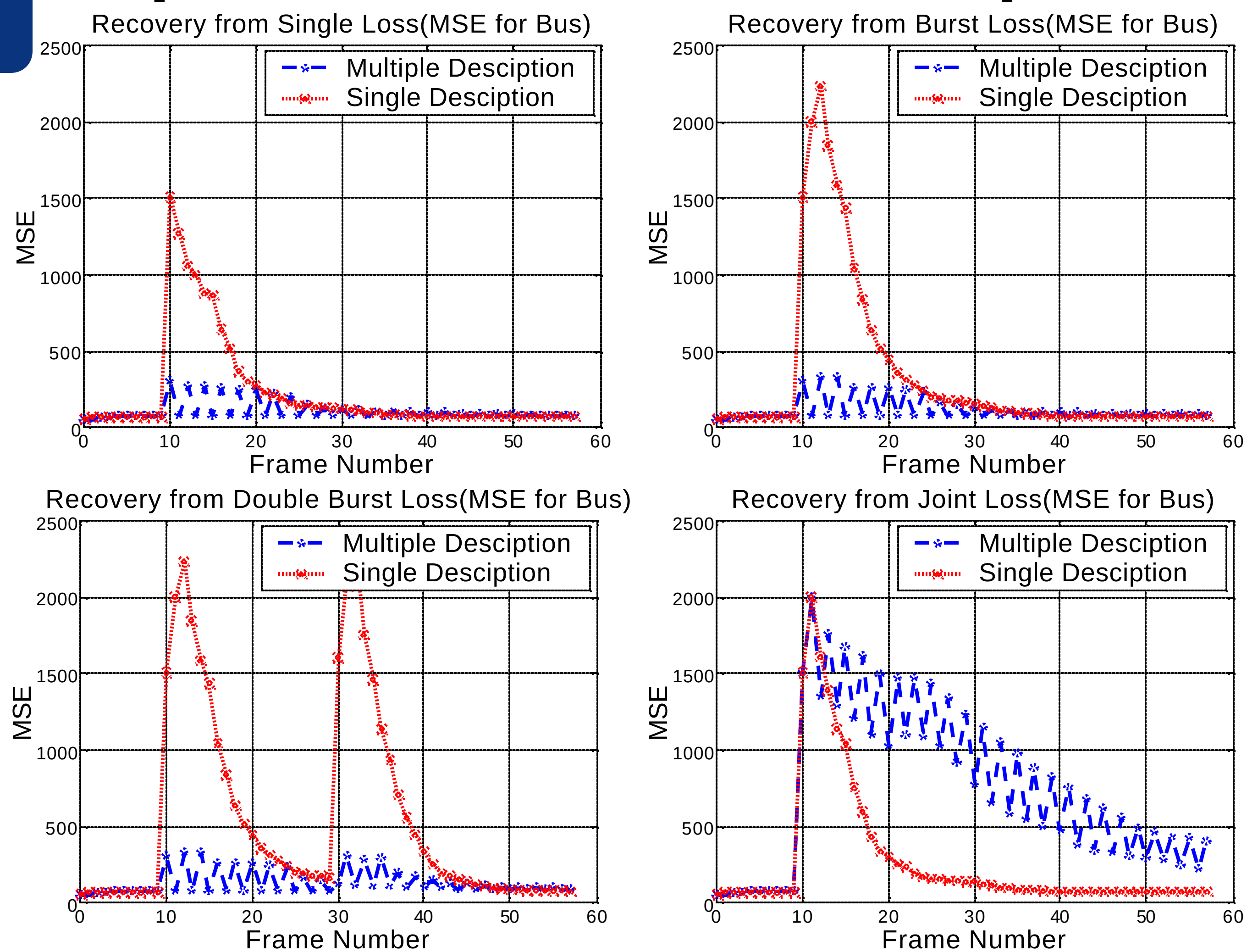
Experimental Results: Bus Sequence

Single Loss

Burst Loss

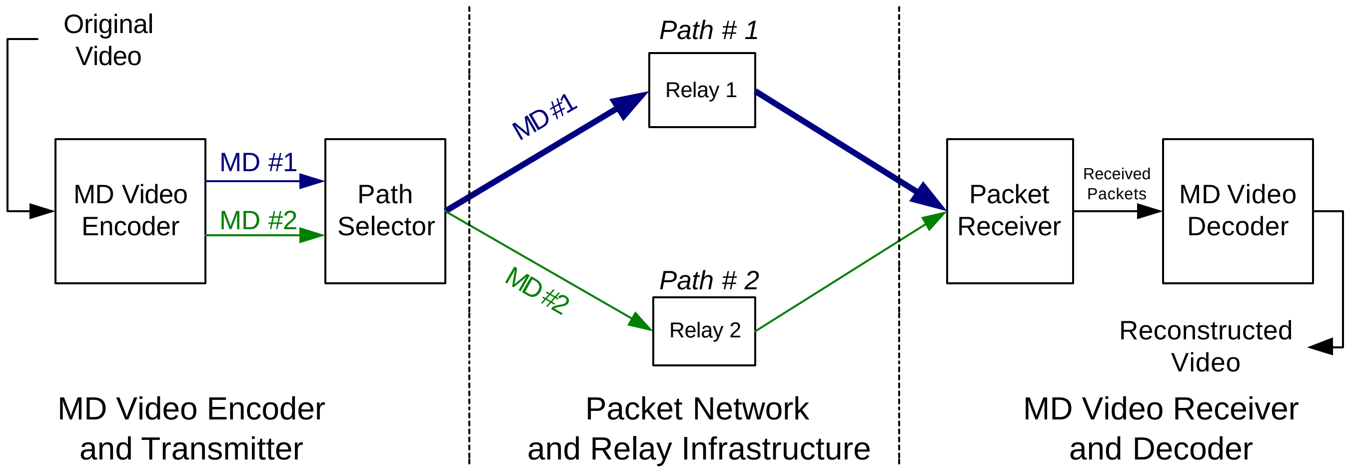


Double burst loss

Simultaneous losses

- SD significantly more vulnerable to losses and length of loss
- MD largely immune to the duration of the loss, as long as both descriptions are not simultaneously corrupted

Unbalanced MD Video Communication



- Problem: Each network path is different and time-varying, therefore the available bandwidth in each path may differ
  - Must adapt the bit rate of each description to the available bandwidth along its path → Unbalanced operation
  - Idea of unbalanced MD coding is well-known, however it is largely unexplored in MD video coding

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Unbalanced MD Video Communications (cont.)

- Can we preserve performance for unbalanced operation over:
  - Clean (error-free) channel
  - Corrupted (lossy) channel
- Methods for adapting bit rate of each description:

	Performance Without loss	Performance With loss
Quantization	Good for small changes (0-10 %), above that possible flicker	Good for small changes (0-10%), above that reduced recovery
Spatial Subsampling	Potential flicker	Potentially reduced recovery
Temporal Subsampling	Good for large range of bit rate changes, non-uniform frame rate maybe OK for medium-high frame rates	Generally good recovery

- Summary: Successful unbalanced MD operation for bit rates of almost 2:1

"Unbalanced Multiple Description Video Communication Using Path Diversity", J.G. Apostolopoulos and S.J. Wee, ICIP, October 2001.

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Recent Related Work

- Real-time voice communication (VoIP) using MD speech coding and path diversity [Liang, Steinbach, Girod; Stanford EE368c 2001; ACM MM'01]
  - Significant reductions in latency & loss rates, and improved VoIP speech quality (PESQ) by exploiting different delay variations in different paths
- Image/video transmission over multi-hop radio environment using route diversity [Gogate, Chung, Panwar, Wang; ICC'99 & preprint]
  - Send packets over multiple paths in a multi-hop wireless environment
  - Video coded with an MD image coder (no error propagation occurs)
- Distributed video streaming [Nguyen, Zahkor; SPIE'02]
  - Conventional SD video delivered over multiple paths provides improved reliability over SD video over a single path

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Modeling MD and Path Diversity Performance

- Goal: Accurate models for predicting and comparing:
  - Conventional single description (SD) over a single path
  - MD video and path diversity

- In the following:
  1. Start simple, with high-level models for SD & MD
  2. Detailed model for SD over single path
  3. Detailed model for MD and path diversity

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Modeling MD and SD Distortion: Start Simple!!!

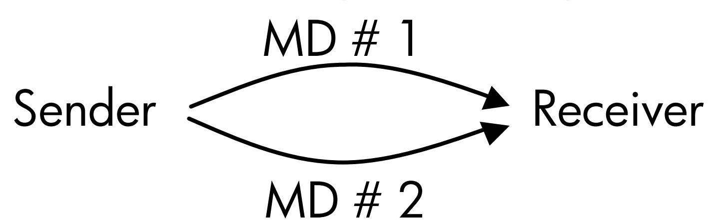
- Distortion for single description (SD) over single path:

Bernoulli Loss Model
- P(loss) = P
- P(no loss) = 1 - P

$$D_{SD} = (1-P)\cdot D_{NoLoss} + P\cdot D_{Loss}$$

Dominant distortion for SD

- Distortion for multiple description (MD) over two paths:



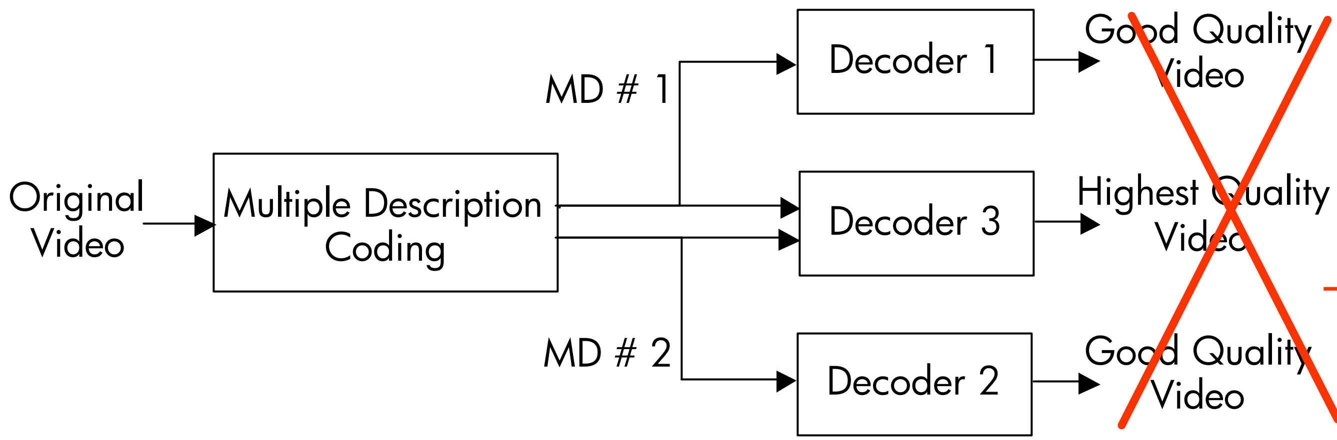
$$D_{MD} = (1-P)^2 d_{NoLoss} + P(1-P)d_{MD\#2} + (1-P)Pd_{MD\#1} + P^2 d_{MD\#1\&MD\#2}$$

Dominant distortion for MD

- MD distortion varies as P^2 while SD varies as P

Modeling MD and SD Distortion: Previous Slide Too Simple!!!

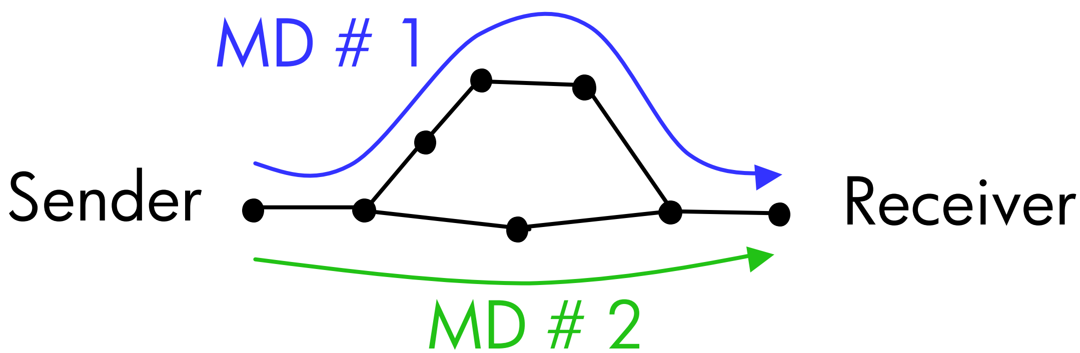
- Previous slide highly simplistic, many issues are ignored
- Source coding:
  - Assumed classic MD coding situation:
    - Completely receive or completely lose each description



Central vs. Side Distortion
→ Incorrect metric!

  - Real world: Partially receive & partially lose each description
    - → Results in error propagation for video
    - → Use state recovery to exploit partial descriptions

Modeling MD and SD Distortion: Previous Slide Too Simple!!!



- Channel:
  - Typically, paths are partially shared and partially not
  - Path may have different lengths
  - Different characteristics for each path
  - Single packet loss and burst losses
- …

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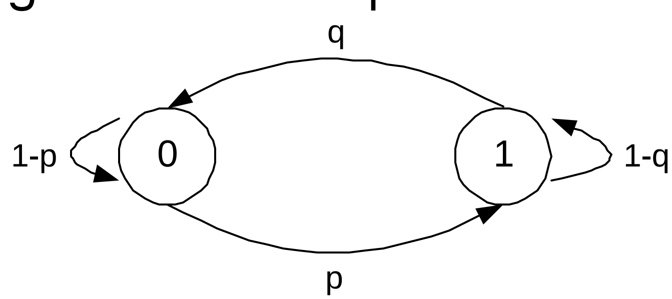
Improved Models

Improved models for estimating SD and MD distortion:

- Source coding
  - Model distortion for all loss events (partial losses of one or both descriptions)
- Channel characteristics
  - Model each path as the concatenation of a number of links
  - Some links are shared (joint), some are not shared (disjoint)
  - Assume each link is independent
  - Assume Gilbert model for each link, where the loss and burst length behavior is parameterized by $\{p_0, q_0\}$



Modeling Single Description over a Single Path

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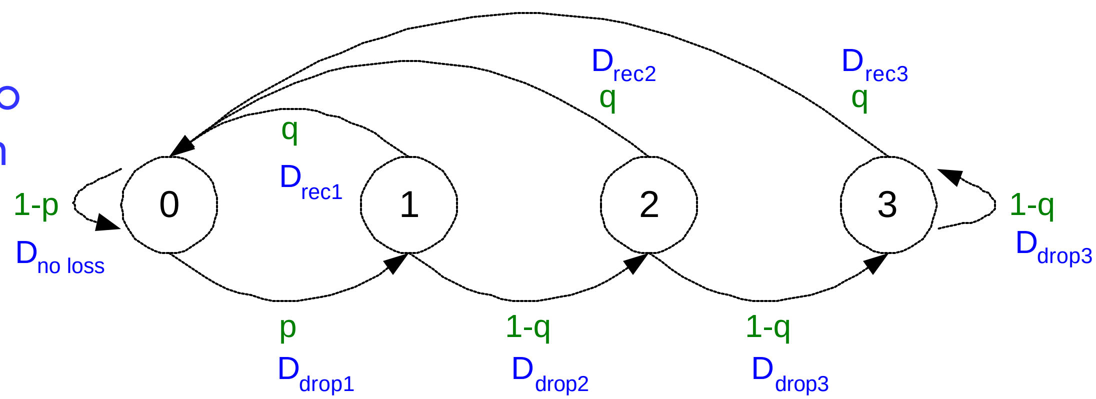
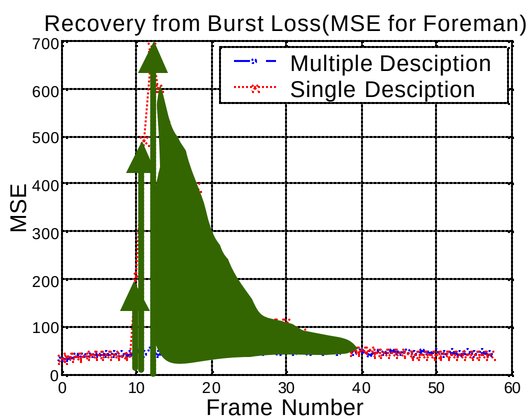
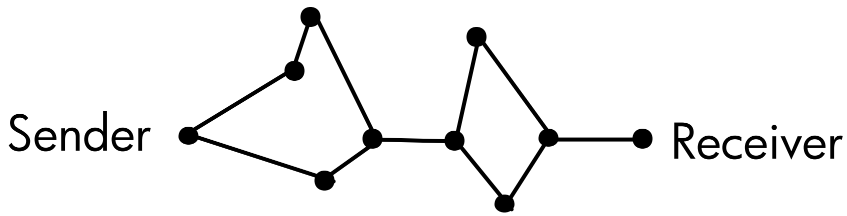
- Goal: Model distortion for SD video over a single path of N links
- End-to-end loss model captured by two-state Gilbert model with different {p,q}
- SD distortion depends on burst length → Capture burst length in model

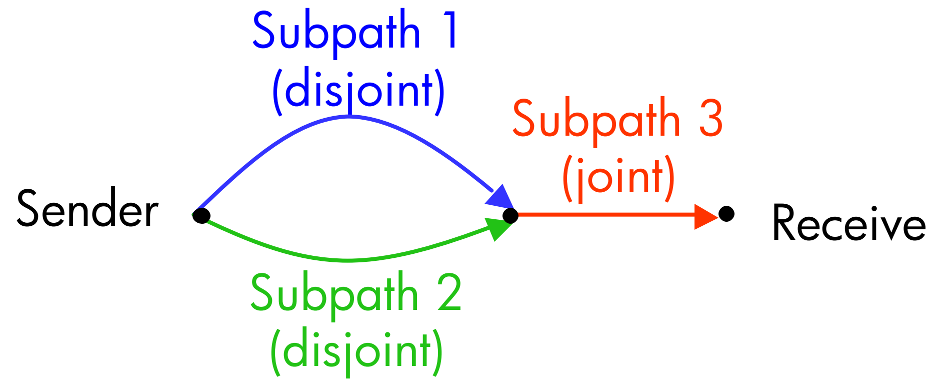
Model for SD Video Over a Single Path





Modeling MD and Path Diversity: Loss Process for Two-Path Diversity





- End-to-end loss process summarized by 3 sets of Gilbert model parameters, corresponding to 3 subpaths:
  - Disjoint links along path 1: Subpath 1
  - Disjoint links along path 2: Subpath 2
  - Joint links along paths 1 and 2: Subpath 3
- 8-state model, however must account for losses of both streams in joint links, therefore 16-state model
- Summary: Two-path path diversity is accurately modeled by 16-state model and 16x16 state transition matrix

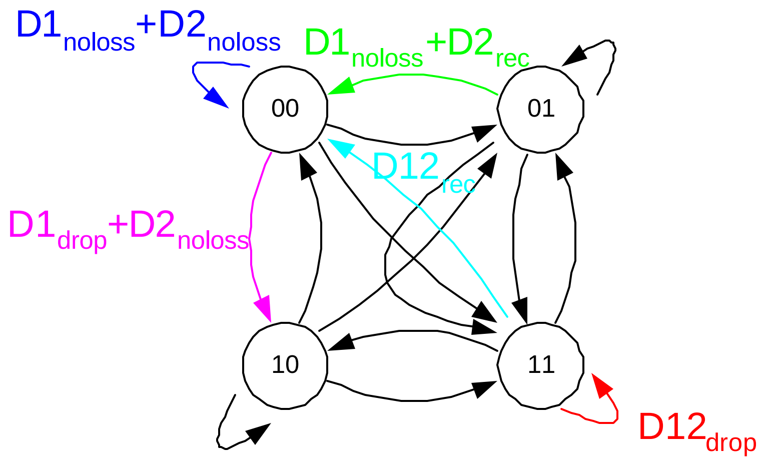
Modeling MD and Path Diversity: MD Distortion Model

- MD distortion depends on whether losses afflict one or both descriptions simultaneously
  - Unlike SD, MD does not depend on burst loss length
- MD video model:
  - Distortion behavior at any instance in time expressed by four states:

MD #1	MD #2	State
OK	OK	00
OK	Loss	01
Loss	OK	10
Loss	Loss	11

Modeling MD and Path Diversity: Summary

Model for MD Video and Two-Path Path Diversity



- Transition probabilities for 4 MD states are a function of transition probabilities of 16-state path diversity loss model
  - Each of the 16 possible transitions corresponds to a different loss event and a different distortion
- Expected distortion can be straightforwardly computed

"Modeling Path Diversity for Multiple Description Video Communication", J.G. Apostolopoulos, W. Tan, S.J. Wee, G.W. Wornell, to appear ICASSP, May 2002.

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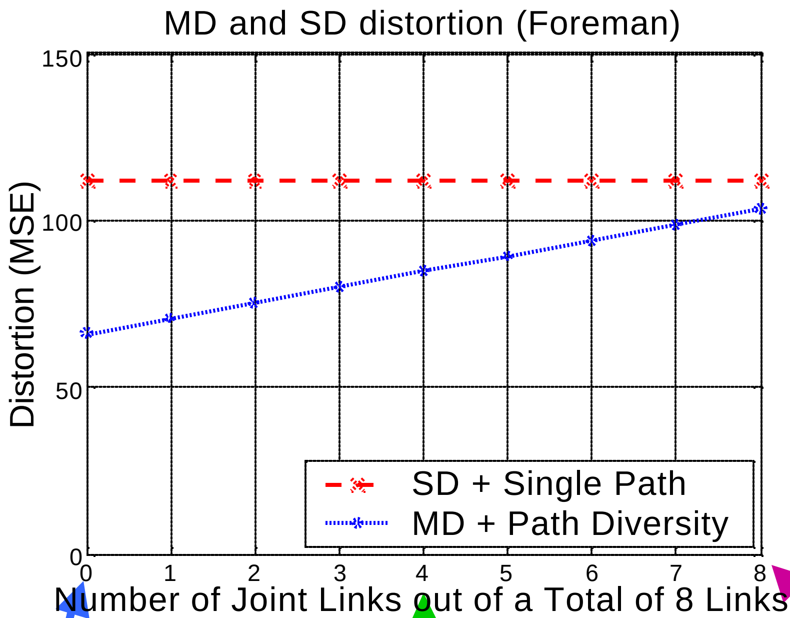
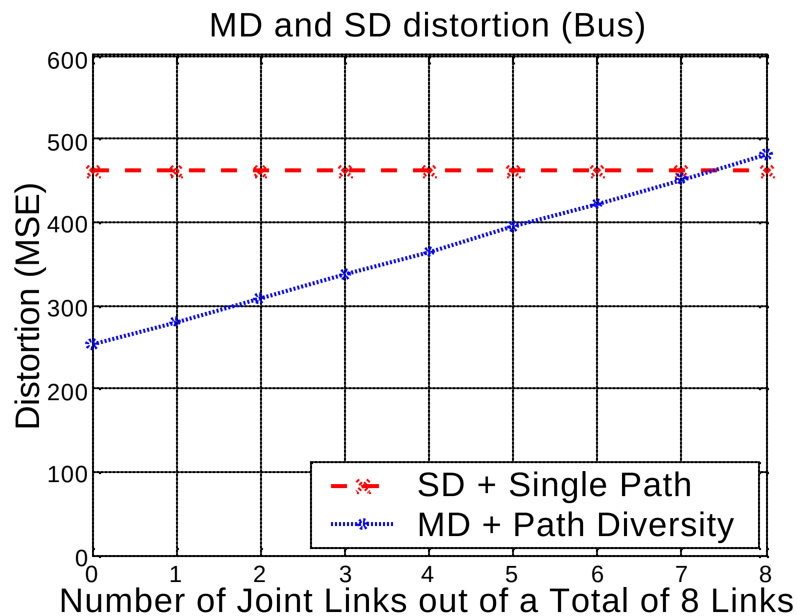
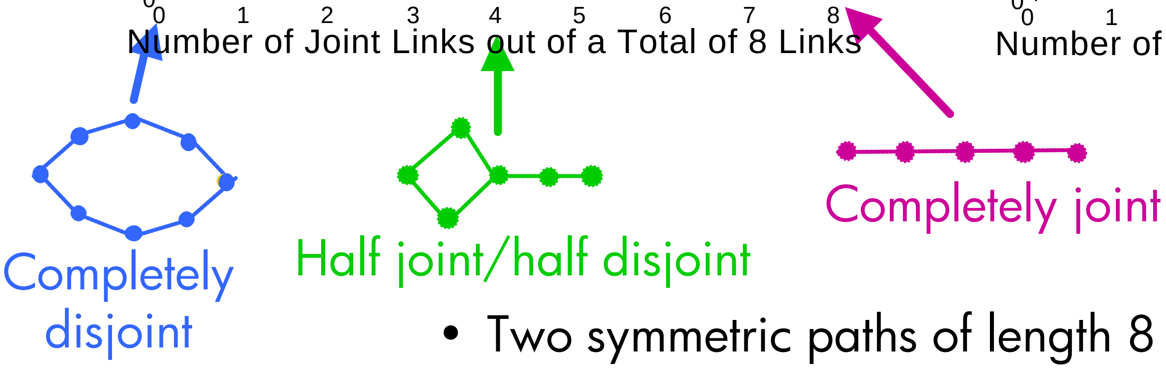
Comparing MD vs SD Performance: Joint vs Disjoint Losses







- Two symmetric paths of length 8 links
- 5 % end-to-end average packet loss rate, average burst length of 1.25 packets (for 30 msec sampling)
- Vary fraction of total number of links that are joint and disjoint
  - Illustrates the effect of joint and disjoint losses

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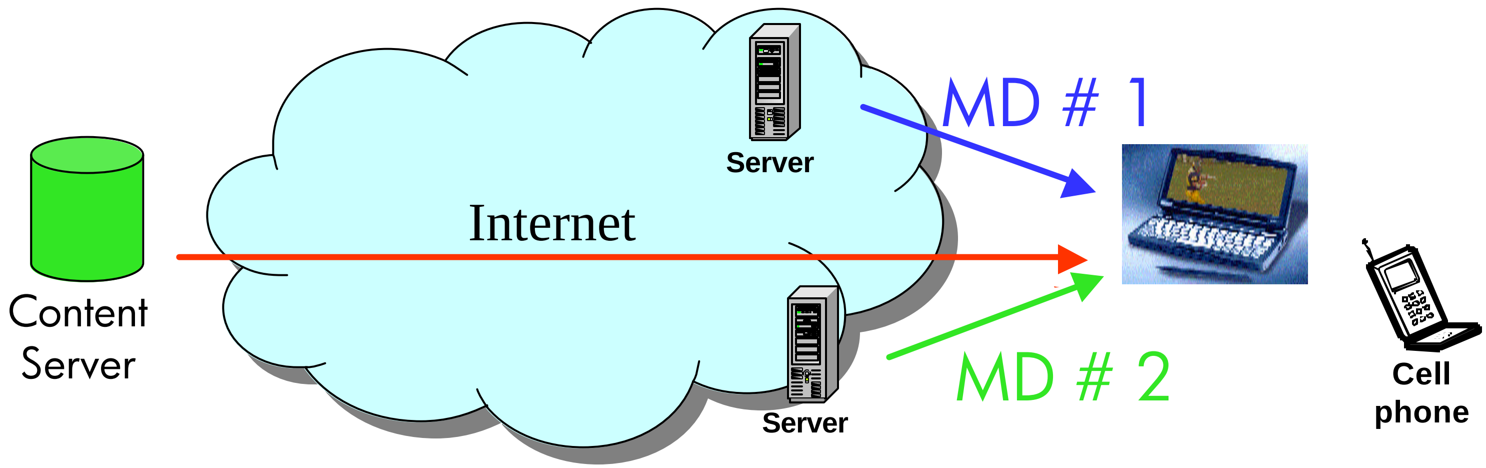
Multiple Description Streaming Media CDN



- MD-CDN: Use CDN to explicitly achieve path diversity
  1. Code media into multiple descriptions
  2. Distribute different descriptions on different servers
  3. Direct each client to multiple nearby servers with complementary descriptions
  4. Client is sent different descriptions over different paths from different servers

"On Multiple Description Streaming with Content Delivery Networks",
J.G. Apostolopoulos, T. Wong, W. Tan, and S.J. Wee, to appear IEEE INFOCOM, June 2002.

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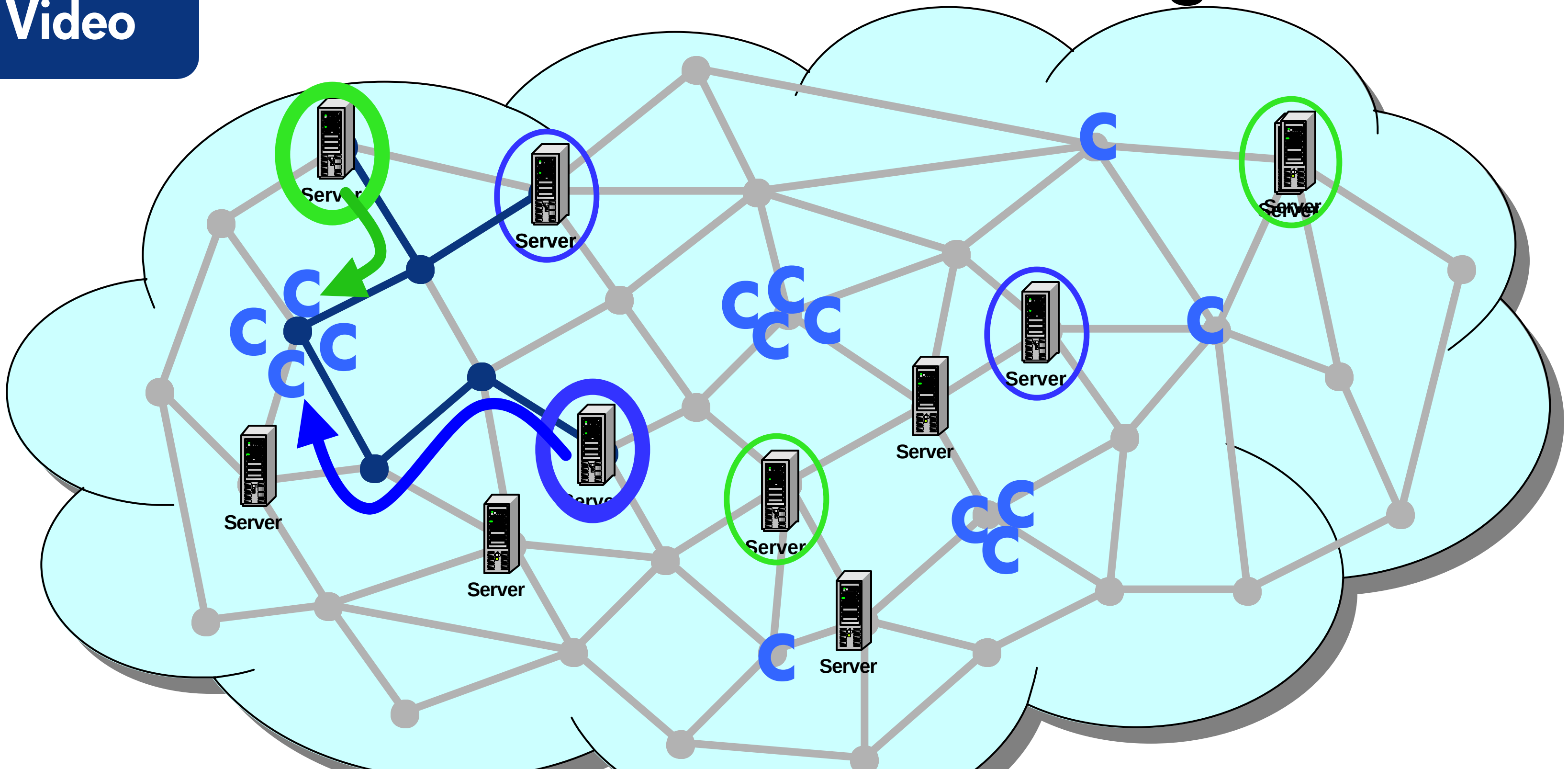
MD – CDN Architecture Design



Three key CDN problems:

1. Where to deploy the servers? (Server Placement)
2. How to distribute the content? (Content Distribution across Servers)
3. How to select for each client the best server? (Server Selection)

Our MD & Path Diversity performance models enable us to attack these problems

Simulation Experiments

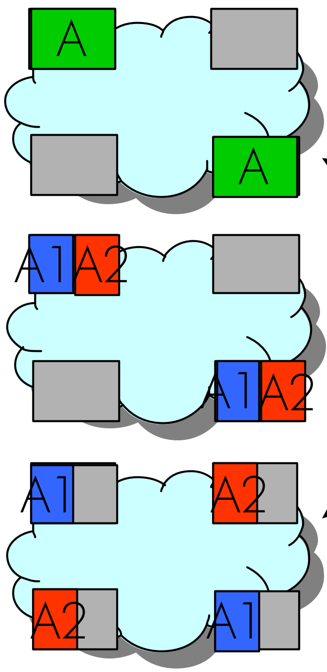
- Examined five topologies:

Name	Type	Date	# Nodes	# Edges
AT&T	ISP	2000	87	195
UUNet	ISP	2001	113	1078
AS	Inter-AS	1999	4830	9078
BRITE-h	Generated	NA	1000	1987
BRITE-f	Generated	NA	1000	1997

- Realistic topology selection and simulation
- Further details available in:

"On Multiple Description Streaming with Content Delivery Networks",
J.G. Apostolopoulos, T. Wong, W. Tan, and S.J. Wee, to appear IEEE INFOCOM, June 2002.

Simulation Experiments (cont.)

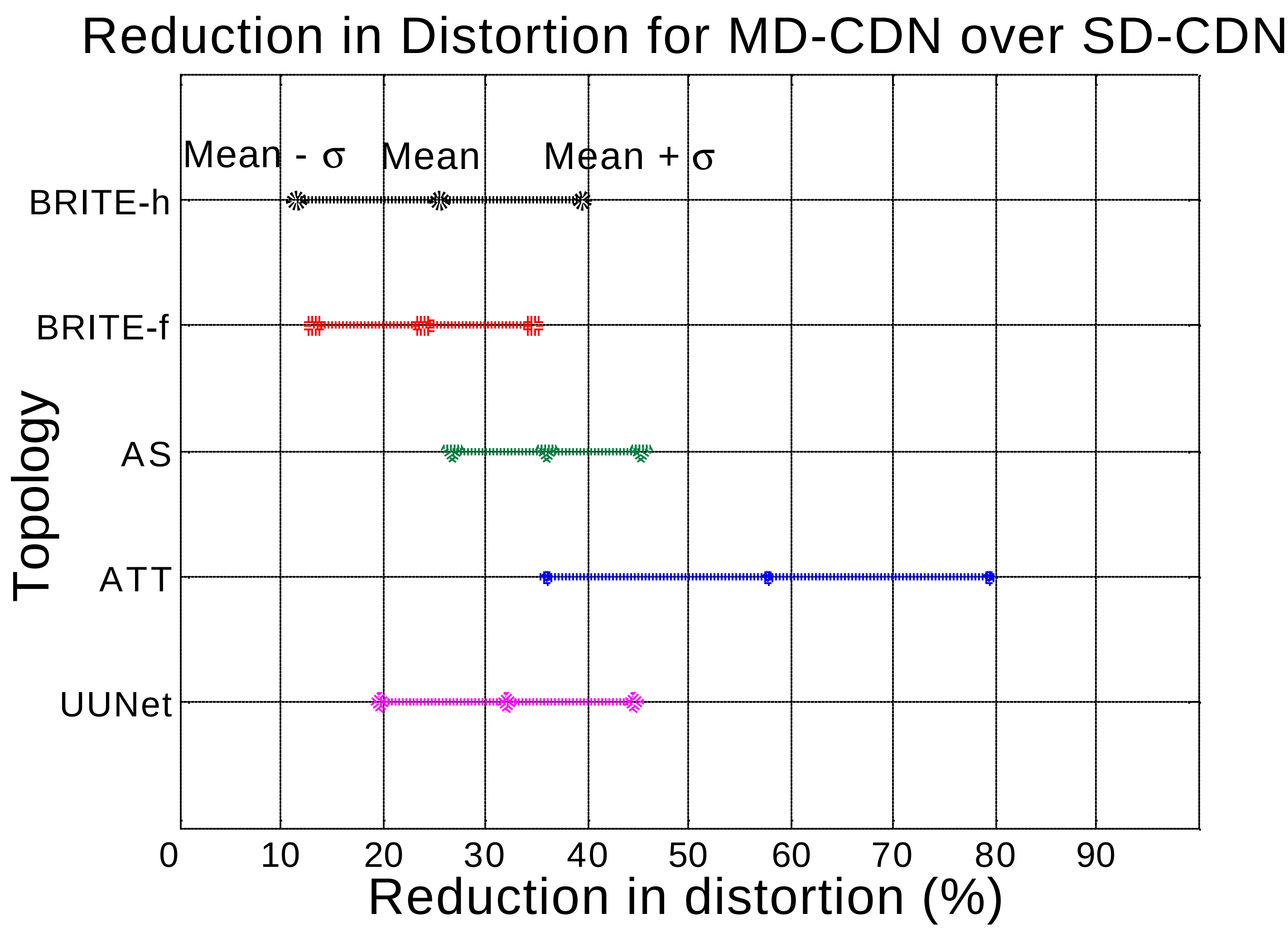


- MD Server Placement Algorithms
  - Edge (nodes with degree of 2-3)
  - Core (nodes with highest degree)
  - IDC (available for AT&T topology)
  - → Above are biased to SD-CDN (minimize distance)
- MD Distribution Across Servers Algorithms
  - SD on randomly chosen half of servers
  - MD-half: MD on same half of servers as SD
    - MD & SD use same servers, same total storage, same total bandwidth to clients
  - MD-all: Randomly place one description on every server
    - Remove constraint that SD and MD use same servers
    - However, total storage and total bandwidth remain the same
- MD Server Selection Algorithms
  - Two distinct shortest paths
  - Minimum expected distortion (optimal selection)

Simulation Experiments (cont.)

- All links are assumed identical to simplify simulations
- Packet loss adjusted in each case to provide:
  - End-to-end average loss rate of 5 %
  - Expected burst loss length of 1.25 packets (30 ms sampling)
- Results presented for difficult Bus sequence
  - (MD is much better for Foreman)
- Biased towards SD-CDN (for IID shortest path algorithm is optimal)
  - Server placement
  - Server selection

Simulation Experiments: Reduction in Distortion for MD-CDN



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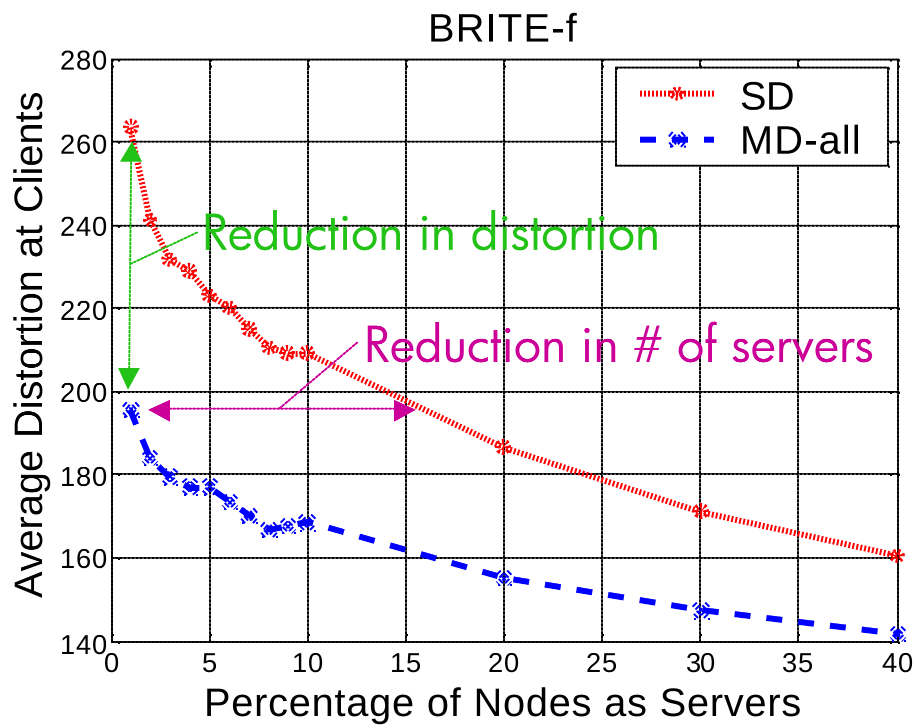
Simulation Experiments: Reduction in Required # of Servers



- MD streaming requires fewer servers to achieve the same distortion as SD streaming
- Even when the CDN is not designed with MD streaming in mind

Summary

- MD video coding & path diversity
  - → Reliable video communication over lossy networks
- Models for accurately predicting performance of
  - – MD video and path diversity
  - – Conventional SD over single path
  - → Realistic metrics for comparison
- Multiple description streaming media CDN (MD-CDN)
  - – 20-40 % reduction in distortion
  - – Significant reduction in required # of servers to achieve given distortion
  - – MD-CDN Summary: Improved performance even when CDN is not designed for MD streaming

Papers available: www.hpl.hp.com/personal/John_Apostolopoulos invent