# *Conductor:* Distributed Adaptation for Heterogeneous Networks


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# Introduction

- Problem: Application behave poorly in highly variable and heterogeneous environments
- Goal: Help applications provide the best possible service to the user given current network conditions
- Approach: Conductor provides coordinated and distributed adaptation of application-level protocols as a transparent middleware service



# The Need for Adaptability

- Networks can be highly variable
  - Bandwidth, latency, jitter, $$, security, reliability
- Applications frequently assume a minimum level of network service
  - Cost vs. benefit imbalance
- Applications should provide a level of service that the network can support

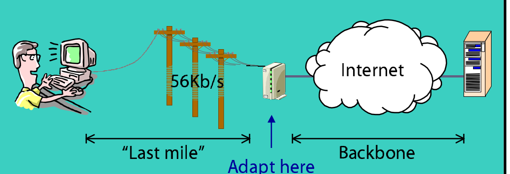


# Enabling Adaptability

- Adapt application-layer protocols from within the network
  - Compress, encrypt, prefetch
  - Distill a video stream to black-and-white
  - Prioritize interactive browsing over software downloads
  - Remove advertisements from web pages
  - Power down wireless interface during predicted query response latency

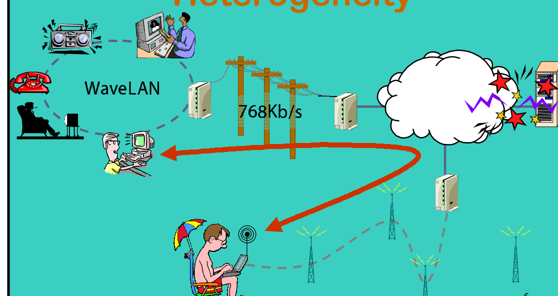


# Trend: Network Heterogeneity






# Trend: Network Heterogeneity



## Distributed Adaptation

- Goal: Help applications provide the best possible service to the user given current network conditions
- Required:
  - Multiple adaptations
  - Distributed within the network
  - Coordinated

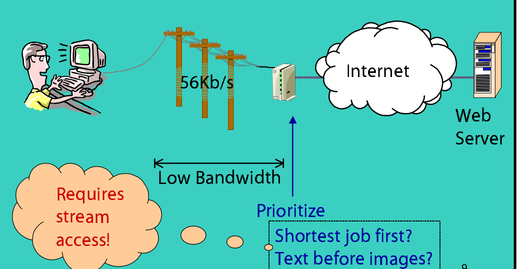


## Case Study #1

Secure, Low-Bandwidth Web Browsing

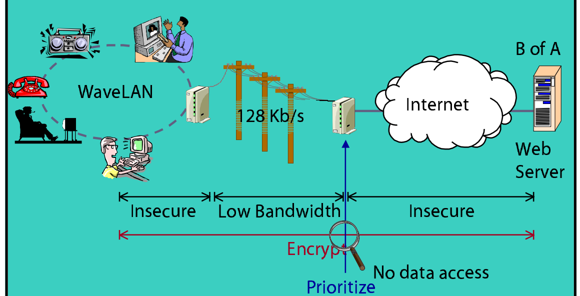


## Case Study #1



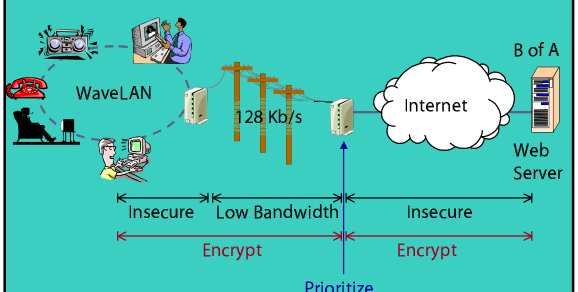



## Case Study #1






## Case Study #1

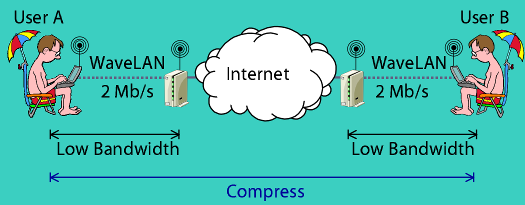





## Case Study #2

Wireless to Wireless Video Streaming

## Case Study #2



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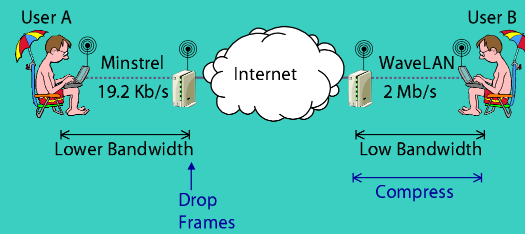




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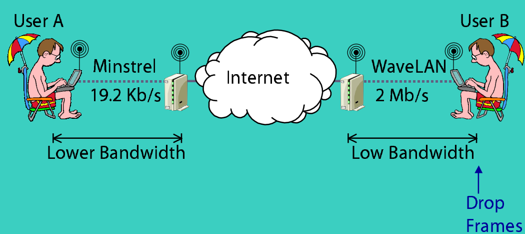




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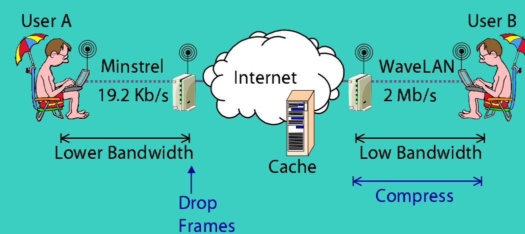
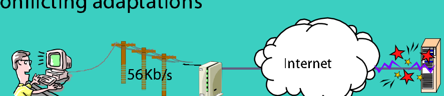





## Deployment Constraints

- Limited node resources
  - Load balancing, palmtops
- Location, location, location
  - Proximity means agility
  - Hardware access
  - Leveraging topology
- Conflicting adaptations






## Adaptation in Heterogeneous Networks

- Must consider end-to-end network characteristics
  - Multiple constrained links
  - Multiple types of constraints
  - Conditions difficult to predict
- Many possible adaptations
- Multiple points of adaptation
- Coordination required!

## Conductor: Architecture Overview …

- Our Approach
- Conductor's Architecture
- Stream Management
- Adaptor Selection
- Security
- Reliability
- Adaptation-aware API



## The Conductor Approach

- Arbitrary (and potentially lossy) adaptation of application-level protocols
  - Reliable connection-oriented streams (TCP)
- Dynamic selection of adaptive code modules at enabled points in the network
  - Conductor is incrementally deployable
- Application transparent, but not user transparent
  - User controllable



## Conductor Architecture

- Components: framework and adaptation modules
- Adaptation framework
  - Transparent interception and routing
  - Node/link status monitoring
  - Centralized planning and deployment
  - Adaptor runtime environment

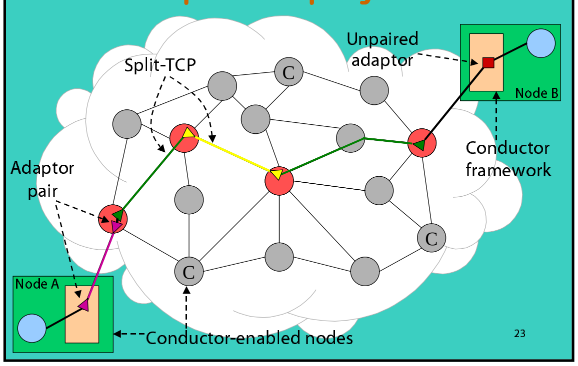


## Conductor Architecture

- Adaptor modules
  - Operate on data stream
    - Arbitrary modifications allowed
  - Easily extensible set
  - Frequently paired
  - Composable
  - Stored on Conductor-enabled nodes

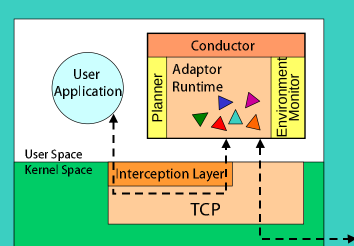


## Adaptor Deployment






## A Conductor-Enabled Node



## Stream Management

- Capture at socket level
  - Maintain existing socket API
  - Route through other Conductor nodes
  - Create transparent split-TCP connection
- Stream identification
  - Port numbers, Protocol identifier, Magic number
  - Dynamic, fine-grained identification by adaptors



## Adaptor Selection

- Goal: Automatically select appropriate sets of adaptors for end-to-end conditions
- Issues:
  - Speed, cost, coordination
- Plan based on distributed information
  - Node and link characteristics
  - Data characteristics
  - User preferences
  - Available adaptors

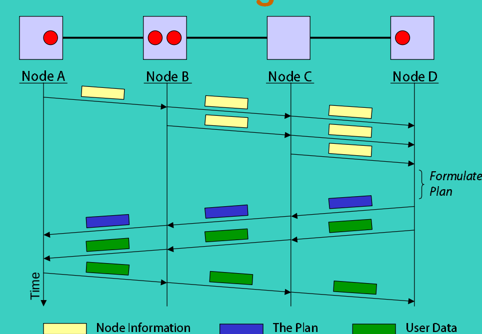


## Planning in Conductor

- Centralized planning
  - Gather all inputs to one location
  - Formulate plan
    - Pluggable architecture
  - Distribute plan
- Reaction to changing conditions
  - Adaptors handle a range of conditions
  - When tolerances are exceeded, replanning occurs



## The Planning Protocol






## What should be protected?

- Protect the nodes from misbehaving adaptors
  - Leverage existing research
- Protect the user from misbehaving nodes
  - Allow only desired adaptations
- Protect the secrecy and integrity of the user data
  - But, still allow adaptation



## Security in Conductor

- Protect planning from untrusted nodes
  - Implicitly trust endpoints
  - Authenticate other nodes and establish trust
- Problem: no ubiquitous authentication mechanism
  - Conductor allows dynamic selection and enforcement of an authentication scheme
- Adapt plaintext only at trusted nodes
  - Encrypt user data between trusted nodes

## Reliable Transmission

- Goal: Provide adaptation for applications that expect reliable delivery
  - TCP, exactly-once delivery of bytes
- Adaptation can violate typical assumption of data immutability
  - Must allow intentional data loss
  - Exactly-once delivery of transmitted bytes makes no sense



## Reliability in Conductor

- Possible failures: nodes, links, adaptors
- New reliability model
  - Exactly-once delivery of semantic elements
- Semantic segmentation
  - Dynamic and automatic stream checkpointing
  - Ensures that adaptation is atomic
  - Provides exactly-once, in order delivery of the adapted stream



## Reliability in Conductor

- Recovering from adaptor failure
  - Identify lost adaptors
    - Maintain distributed state describing adaptor pairing and composition
  - Restore adaptor consistency
    - Adaptor state is lost
    - Cannot just replace failed adaptor, in the general case
    - Remove paired and composed adaptors
  - Replan and redeploy as required



## Adaptation Aware Apps

- Conductor provides transparency through automatic services:
  - Interception, planning, reliability, adaptation
- But application knowledge can be useful
- An API can give some apps more control
  - Select and control adaptors
  - Select trusted nodes
  - Provide data for retransmission
- The best of both worlds



## Evaluating Conductor

- Effective delivery of adaptation
  - Significant benefit in three case studies
  - Low overheads
  - Demonstration of failure recovery
- Office deployment
  - Daily use for POP3 protocol
- A platform for distributed adaptation
  - Beta software release
    - http://fmg.cs.ucla.edu/Conductor
  - A basis for further research



## In Greater Detail …

- Conductor Reliability
- Conductor Security

## Reliability in Conductor

- End-to-end connection built using multi-split-TCP
  - Reliability between points of adaptation
  - Leverage existing technology
  - Adaptation at each node independent of TCP
- Node and link failures detected as TCP connection failures

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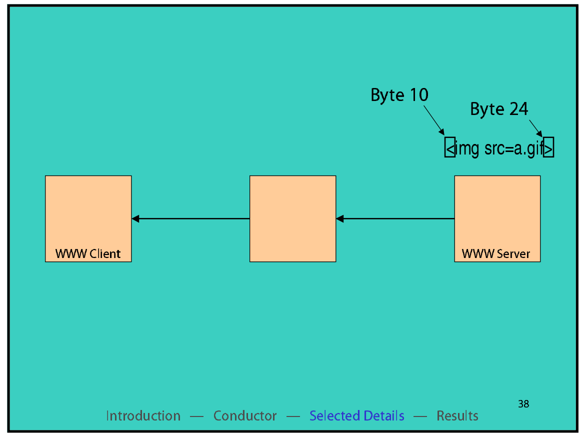


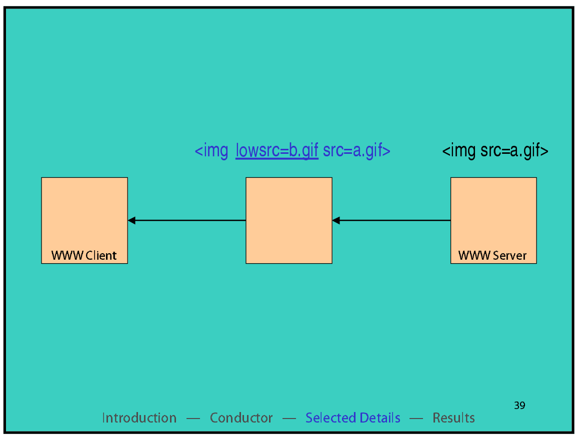


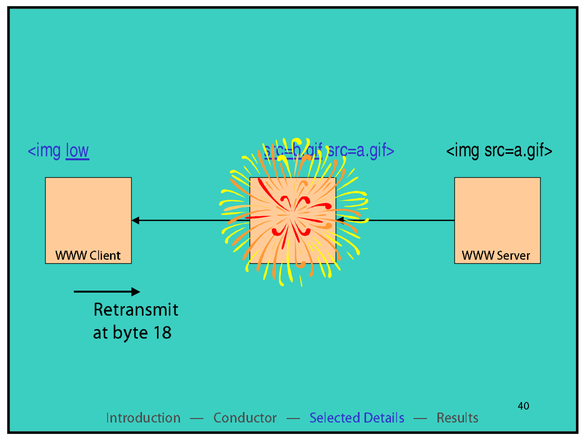


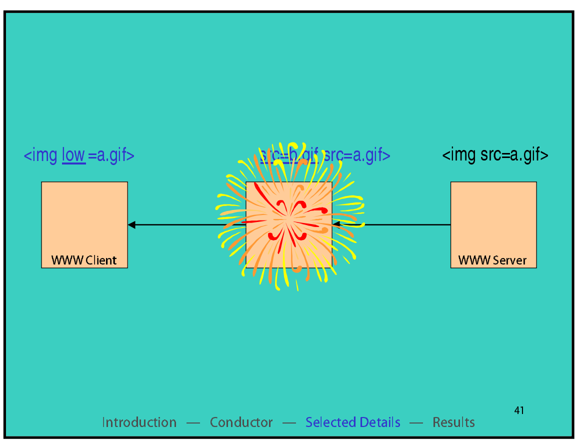


## Reliability in Conductor

- How do we know if any data was lost?
- Was adaptation complete?
- From what point should transmission be restarted?
  - » Need a new unit of retransmission
  - » Maintain some correlation between pre- and post-adapted data

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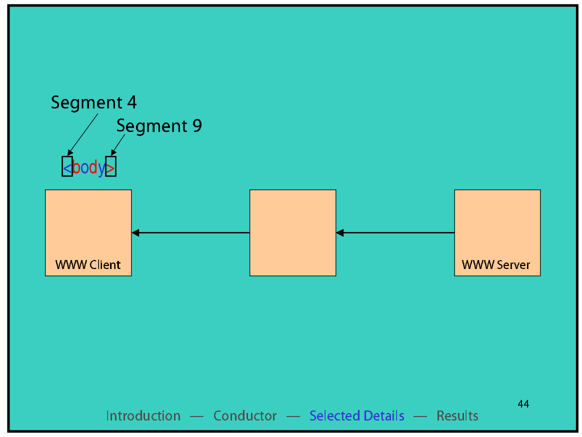
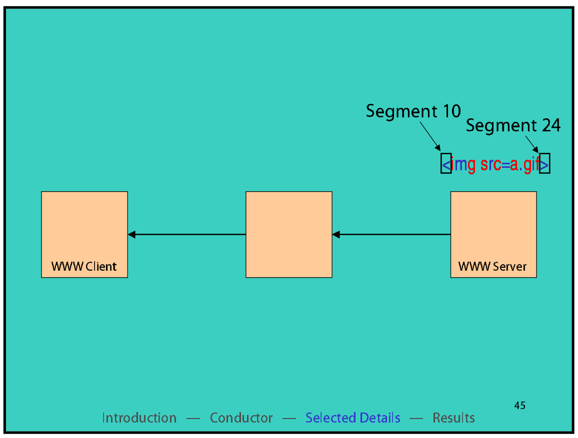
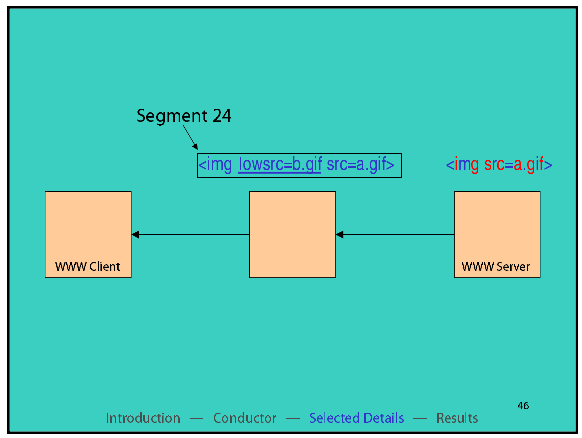
# Reliability in Conductor

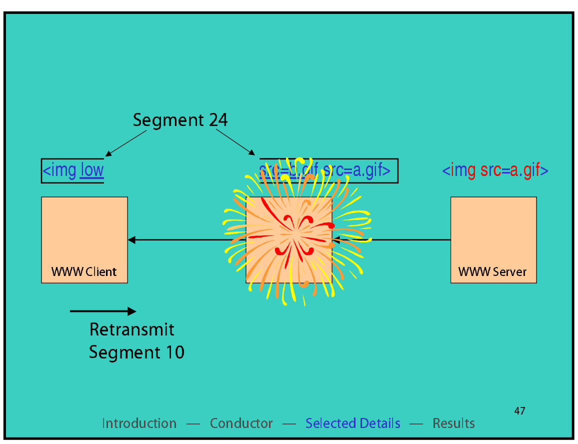
- *Semantic Segmentation*: a semantically meaningful unit of retransmission
  - Divide stream into semantic units
    - Dynamically, based on data type and adaptation
    - No application hints required
  - Preserve semantic meaning of each segment end-to-end
    - Maintained by segment combination
  - Adaptors can express recovery constraints

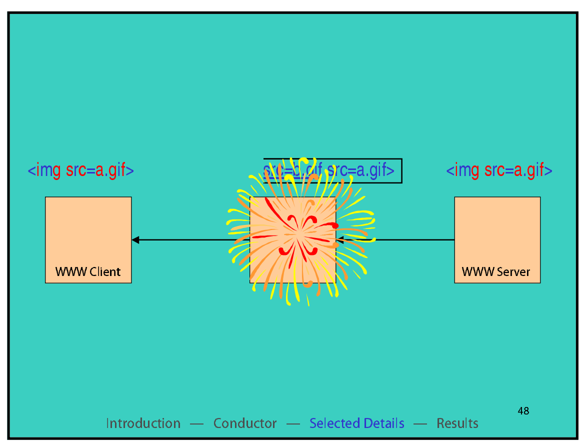




## Rules of Segmentation

- Start with one byte segments
- Constrain each stream modification to one segment
- Combine segments where necessary
  - New segment contains combined semantic meaning
  - Assign segment ID from last combined segment
- Final delivery of complete segments only

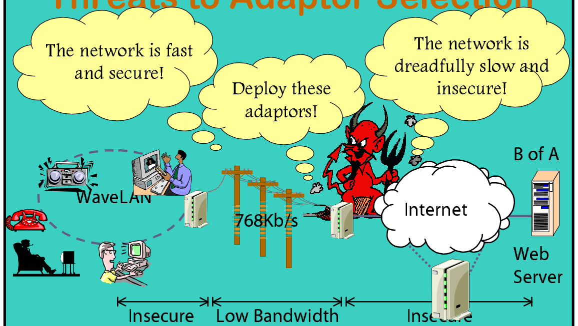


## Benefits of Segmentation

- Service guarantees:
  - Transaction-like adaptation (all or nothing)
  - Exactly-once, in-order delivery of some form of each semantic element
- Adaptors can express appropriate points for adaptation changes



## Threats to Adaptor Selection






## What nodes can we trust?

- Various levels of trust possible
  - See or modify plain text
  - See or modify encrypted text
  - None
- Implicitly trust endpoints
- Trusting other nodes
  - Requires some type of authentication
  - Static list, dynamic trust model



## Complications of Distributed Adaptation

- Users require different levels of security
- Adaptation may span administrative domains
  - No ubiquitous authentication infrastructure
  - Many choices; how do we agree securely?
- Must allow *limited* stream access within the network
  - Only desired adaptations
  - Typically restricted to trusted nodes



## Authentication

- Goals:
  - Verifiable node identity
  - Digital signature capability
- Plug-in modules provide various authentication schemes
  - Null
  - Public-key based: tree, chain of trust
  - Kerberos based

## Secure Planning

- Self-enforcing scheme selection
  - The client selects an authentication scheme
  - The server returns a signed message indicating the scheme used
- Authentication
  - Each node authenticates to the planner
  - The planner authenticates to each node
- Secure planning
  - Planning information is signed by the sender
  - Use only authentic information from trusted nodes
  - The plan is signed by the planner



## Virtual Link Encryption

- Allow plaintext adaptation only at trusted nodes
- Encrypt between points of adaptation
  - Use encryption adaptors
- Requires:
  - Selection of trusted nodes
  - Encryption adaptor selection and deployment
  - Secure key distribution



## Research Results …

- Performance
- Comparison with other research
- Key contributions
- Conclusions



## Selected Performance Results

- Overheads reduce the potential benefit of adaptation
  - Conductor has low startup and data handling costs
- The framework is only useful if adaptors can provide real benefit
  - Conductor provided significant benefit in our case studies



## Conductor Overheads

- Data handling overheads
  - Reduction of throughput and latency over 100 Mbps Ethernet

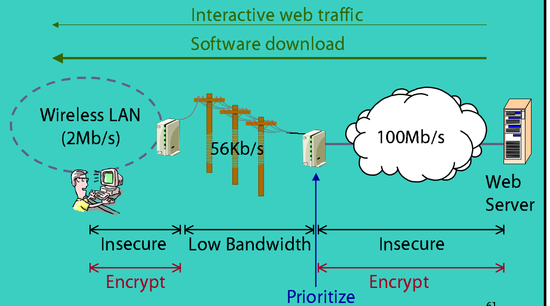
| | Per enabled node | Per *null* adaptor |
|---|---|---|
| Throughput Reduction | 0.046% | 0.004% |
| Latency Increase | 270 μsec | 40 μsec |



## Conductor Overheads

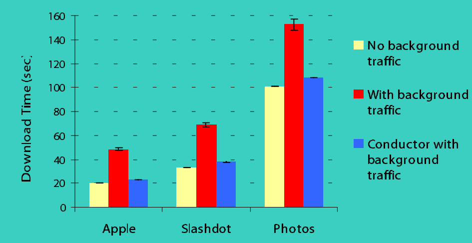
- Startup overheads
  - ~10 ms per enabled node
  - ~250 μs per *null* adaptor
- Small for connections that last a few seconds or more
- Offset by the benefits of adaptation

## Case Study # 1



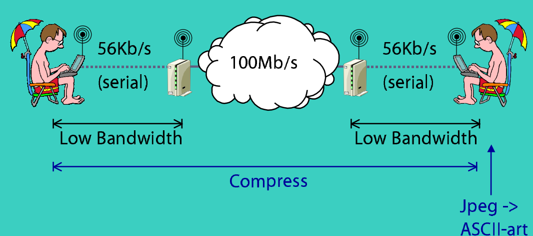



## Results for Case Study #1



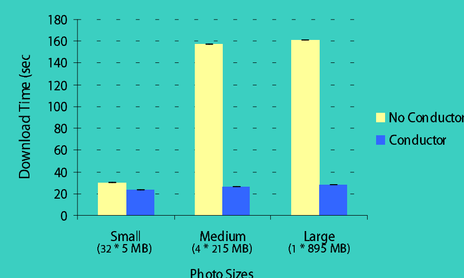



## Case Study #2






## Results for Case Study #2






## Key Properties of Conductor

- Automatic and transparent
  - No user or application action required
- Distributed and coordinated
  - Multiple adaptations at multiple locations
- Incrementally deployable
- Extensible set of adaptations
- Reliable and secure



## Other Approaches

- Situation-specific applications
  - Palm clipping apps
  - Text-based web browsers

» May require specialized applications
» Requires user diagnosis and intervention

## Other Approaches

- Adaptable applications
  - Odyssey [Noble]
  - Rover [Joseph]
  - Application partitioning [Kottmann][Watson]

    » Requires application modifications

    » Application writer must foresee and understand possible network conditions

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## Other Approaches

- Adaptation as a network service
  - Boosting existing protocols
    - Snoop [ Balakrishnan ]
    - Protocol Boosters [ Bellcore /U. Penn]
  - Protocol Transformers
    - Transformer Tunnels [ Sudame , Badrinath ]
    - Proxy architectures [Fox, Gribble] [ Zenel ]
  - Active Networks

    » Lack coordination and reliability needed for arbitrary multipoint adaptation

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## Key Contributions

- Transparent adaptation is desirable and achievable
  - Does not rule out adaptation-aware apps
- Significant benefit to raising the level of services within the network
  - In an incrementally deployable manner
- Reliable delivery of adapted data
  - Allows reliability despite stream modification

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## Key Contributions

- Security architecture to maintain user control over distributed adaptation
  - With pluggable, self-enforcing authentication
- A working platform for distributed adaptation
  - In daily use
  - A basis for additional research

Introduction — Conductor — Selected Details — Results



## Conclusions

- Conductor extends adaptation …
  - Automatic, application unaware
  - Distributed: multi-site, coordinated
- Key enabling services
  - New reliability model: *semantic segmentation*
  - Framework for automatic planning
  - Security
  - API for adaptation-enabled applications
- Conductor: effective distributed adaptation made easy

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