Distributed Adaptation for Heterogeneous Networks

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Roadmap

- Adaptation and network heterogeneity
- Our approach: distributed adaptation
- Advantages of distributed adaptation
- Conductor design and implementation
  - Architecture
  - Planning
  - Stream Management
  - Security
  - Reliability

The Need for Adaptability

- Networks: not always fast and free
  - Bandwidth, latency, jitter, $\$, security, reliability
- Applications typically assume a minimum level of network service
  - Cost vs. benefit imbalance
- Goal: applications should provide gracefully degraded service

Adaptive Software:

Software that can tailor its services to constraints in available resources and user expectations.

Enabling Adaptability

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

Adaptation in Heterogeneous Networks
- Multiple constrained links
- Multiple types of constraints
- Conditions difficult to predict
- Many possible adaptations
- Many possible locations for adaptation

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Distributed Adaptation
- Goal: allow applications to degrade gracefully in heterogeneous networks
- Required:
  - Multiple adaptations
  - Distributed within the network
  - Coordinated

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

- New reliability model required
  - Exactly-once delivery of bytes no longer makes sense
- Enable coordinated adaptation
  - Multi-node planning in a low-performance network
- Security without de facto infrastructure
  - Protect control over adaptation without a ubiquitous authentication architecture

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Case Study #1

Secure, Low-Bandwidth Web Browsing
Case Study #2

Wireless to Wireless Video Streaming

Case Study Results

- Multiple adaptations
- Multiple points of adaptation
- Coordination required!!
- Must understand end-to-end network characteristics
Adaptation Deployment Constraints

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

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

Other Approaches

- Adaptation as a network service
  - Boosting existing protocols
    - Snoop [Balakrishnan], Protocol Boosters [Mallet]
  - Protocol Transformers
    - Transformer Tunnels [Sudama, Badrinath]
    - Proxy architectures [Fox, Gringle] [Zemel]
  - Active Networks
    - Lack coordination and reliability needed for arbitrary multipoint adaptation

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Conductor Architecture

- Components: framework and adaptation modules
- Adaptation framework
  - Transparent interception and routing
  - Node/link status monitoring
  - Distributed 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

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 and Adaptation

- Possible failures: adaptors, nodes, links
- Failure modes
  - Potential data loss
  - Partial adaptation of data
  - Lost adaptor state
  - Adaptor consistency

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

Reliability in Conductor

- How do we know if any data was lost?
- From what point should transmission be restarted?
  - Need a new unit of retransmission
  - Maintain some correlation between pre- and post-adapted data
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
  - Not reversible
  - New segment contains combined semantic meaning
- Final delivery of complete segments only

Reversing Segmentation
- With lossy adaptation, segments must remain until delivery
  - Must handle this case
- Lossless adaptation potentially allows original segmentation to be restored
  - A possible optimization

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

Adaptor Selection
- Goal: Select an appropriate set of adaptors for end-to-end conditions
- Requires a planning capability
- Issues:
  - Speed
    - Planning must occur before data flows
  - Cost
    - Likely presence of low-quality link
  - Coordination
    - Local decisions are not always best
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

Planning in Conductor

- Benefits:
  - Only requires one round trip latency
  - Can plug in any "plan formulation" code
    - Static
    - Template based
    - Heuristic search based

Securing Distributed Adaptation

- Goals:
  - Maintain endpoint control over adaptor selection and deployment
  - Protect user data
- Key difficulties:
  - Cross-domain node participation
  - No ubiquitous authentication mechanism
  - Varying user requirements

Security in Conductor

- Solutions:
  - Security monitor controls planning messages
    - Messages can be authenticated
    - Dynamically pluggable authentication scheme
    - Default at an endpoint
    - How do we ensure everyone uses the same authentication scheme?
  - Encryption adaptors protect user data
    - Still need secure key distribution
Security in Conductor

- Authentication schemes
  - None
  - Public key encryption
    - Hierarchical key service
    - Chain of trust
  - Kerberos
- Key distribution
  - Based on authentication scheme

Implementation Status

- Stream management
  - Interception based on port number
  - Routing based on underlying routing
- Reliability
  - Semantic segmentation implemented
  - Adapter API
  - Recovery protocol: partially implemented

Implementation Status

- Planning
  - Information gathering protocol: implemented
  - Simple planner and environment monitor
- Security
  - Security architecture: implemented
  - Several authentication mechanisms
  - Sample encryption adaptors: implemented

Measurement of Success

- Effectiveness
  - Construct examples similar to case studies
- Low overhead
  - Measure overhead when adaptation is not required
- Complete services
  - Dynamic demo: automatically deploy, respond to drastic changes, cope with failure

Measurement of Success

- Usability
  - Everyday use in a heterogeneous office environment
Schedule

<table>
<thead>
<tr>
<th>2011</th>
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<tbody>
<tr>
<td>Sep</td>
<td>Initial Office Deployment</td>
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<tr>
<td>Oct</td>
<td>Adaptor suite</td>
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<tr>
<td>Nov</td>
<td>Development: Dynamic planning</td>
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<td>Dec</td>
<td>Recovery protocol</td>
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<td>Jan</td>
<td>Dynamic Demo</td>
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Contributions of This Work

- Design: architecture to make distributed adaptation possible
- Technical: new model and algorithms for reliability in the face of adaptation
  - Semantic Segmentation
- Engineering: a deployable system
- Demonstration: fully application-unaware adaptation is feasible

Conclusions

- In heterogeneous networks distributed adaptation enables graceful degradation
- Conductor enables distributed adaptation
  - First design and implementation of distributed adaptation
  - Reliability model compatible with adaptation
  - Architecture for coordinated adaptation
  - Trusted coordination for disjoint nodes