Distributed Rate-Distortion Optimization for Rateless Coded Scalable Video in Mobile Ad Hoc Networks

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Motivational Examples

- Potential Applications for Mobile Ad Hoc / Multi Hop Networks:
  
  - Civilian
    - Short-living topologies, when building up infrastructure is too expensive for public events / community services (e.g. 3GPP push services)
    - Extension of wireless coverage of infrastructure networks (e.g. ongoing work on IEEE 802.16j multi-hop relay mode for WiMAX)
    - Mobile access points (802.11s) reduce installation costs
  
  - Search and rescue
    - Emergency/disaster area communication
Mobile Ad Hoc Networks (MANETs)

- MANET routing on top of ad hoc/mesh networks, such as 802.11

- Challenges:
  - Routing
    - Link failures more frequently than in the infrastructure-based networks
    - High mobility → frequent route repairs
    - Possible (high) delay associated with route repair
  - Network separation
    - Physical limitation of network topology

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Impacts on Video Streaming in MANETs

- **Key problem: High route loss probability**

- **In a loaded network: Delay issues and throughput variation**
  - Using many hops → large delay on streams from certain sources
  - Throughput is heavily affected by inter-node interference and number of hops

- **Packet losses**
  - System/architecture dependent – but will in any case happen in congestion cases

→ **Results in frequent video play out interruptions or decoding errors for real-time streaming**
Using multiple servers increases robustness in source connectivity

- RAPTOR codes allow distributed reception of the media data
- Scalable Video Coding enables graceful degradation behavior
Raptor Codes

- **Advantages:**
  - Reduced decoding complexity
  - Generating a ‘huge’ number of encoding symbols from a finite number of source symbols
  - Based on embedded Fountain code
  - Good performance in terms of symbol overhead
  - Transmission of Encoding Symbol Identifier (ESI) for reconstruction of XOR equation at decoder

Ref.: Digital Fountain
Decoding of fountain codes is possible from *different encodings*

- Each different encoding is called a *fountain*

- Use different random seeds for the Raptor encodings, so that the encoding symbols from the different encodings will be different with high probability

- Useful in peer-to-peer and multi server scenarios
Scalable Video Coding (SVC)

- SVC extension of H.264/AVC
- H.264/AVC backward compatible base layer
- Three types of scalability:
  - Temporal Scalability: Hierarchical prediction structures using B-/P-pictures
  - Spatial Scalability: Interlayer prediction of up-scaled residual, intra, motion
  - SNR Scalability: Interlayer prediction of residual, intra and motion data

SNR scalability - encoder structure:
**SNR fidelity scalability (MGS)**

- **Stream rate adaptation scheme:**
  - dropping temporal resolutions of enhancement layer
Results: Single Source with Connection Loss

- Using one source in case of connection loss
Results: Multi Source with Connection Loss

- Using multiple sources with SVC and Raptor in case of connection loss
The Adaptive Approach

- **Distributed rate-distortion optimization**
  - Combination of local optimizations at clients and overlay relay nodes

- **Reduce traffic on individual links**
  - Traffic balancing in the mesh network

- **Attempt to maintain resilience towards link loss, but approach single-server bandwidth efficiency**
  - FEC redundancy against packet loss only
Peer-to-Peer like MANET scenario
Rateless-encoded Scalable Video Coding

RSVC encoding:

Scalable video bit-stream (source block (SB) with $K_l$ source symbols per layer $l$):

<table>
<thead>
<tr>
<th>Layer</th>
<th>Source Symbols</th>
<th>Raptor Encoded Symbols</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 2</td>
<td>1 2 3 4 5 6 7 ... n_l</td>
</tr>
<tr>
<td>1</td>
<td>1 2</td>
<td>1 2 3 4 5 6 7 ... n_l</td>
</tr>
<tr>
<td>L</td>
<td>1 2</td>
<td>1 2 3 4 5 6 7 ... n_L</td>
</tr>
</tbody>
</table>

$\text{timeframe } t_{SB}$

RSVC transport:

Network stream(s) from source 1
Network stream(s) from source 2
Network stream(s) from source S

Client

Condition for successful decoding for layer $l$:

$$k_l \geq \sum_{s=1}^{S} \hat{n}_i^s$$

$K_l \geq k_{\text{min}}$
Let overlay relay nodes perform optimization tasks

- Local network conditions (cross traffic, congestion)
- Signal characteristics of media stream within RTP packets
- Taking into account: Connectivity of connected clients
Rate-distortion Optimization

- **Share the limited bandwidth available at overlay nodes**
  - Problem formulation:
    Minimize the cumulative sum of distortions experienced at connected clients
    
    $$\min_{\{\Delta r_{s \rightarrow 1}, \Delta r_{s \rightarrow 2}, \ldots, \Delta r_{s \rightarrow N-1}, \Delta r_{s \rightarrow N}\}} \left( \sum_{n=1}^{N} D_n \left( G_{n, \text{opt}}(\Delta r_{s \rightarrow n}) \right) \right)$$

    where goodput $G$ is given by
    $$G_n = \sum_{s=1}^{S} (1 - \gamma_{s \rightarrow n}) r_{s \rightarrow n}$$

    $\gamma_{s \rightarrow n}$ Packet loss fraction on path from source peer $s$ to client peer $n$
    $r_{s \rightarrow n}$ Sending rate from source peer $s$ to client peer $n$
Rate Allocation from Relay Peers

- Based on rates allocated from relay peers, client peers request rates of the different video layers/fountains
  - Minimize distortion in decoded video (carry R/D information in Raptor packets)
  - Minimize probability of decoding failure as result of route loss

Example:

<table>
<thead>
<tr>
<th>Rate available from source peer A</th>
<th>Rate available from source peer B</th>
<th>Rate available from source peer C</th>
</tr>
</thead>
<tbody>
<tr>
<td>base layer</td>
<td>enh. layer 1</td>
<td>enh. layer 2</td>
</tr>
<tr>
<td>(100% of base layer, 25% of enh. layer 1)</td>
<td>(75% of enh. layer 1, 70% of enh. layer 2)</td>
<td>(75% of enh. layer 2, 100% of enh. layer 3)</td>
</tr>
</tbody>
</table>
Example

- Client peer c₃ requests stream (City) from source peer i₂,₁
- After 20 seconds, c₁ requests stream (Harbour) from both i₁,₁ and i₂,₁
- After 40 seconds, c₂ requests stream (News) from i₁,₁

Rate-distortion Optimized Sharing

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Rate--distortion Optimized Sharing
Example

- Client peer $c_3$ requests stream (City) from source peer $i_{2,1}$
- After 20 seconds, $c_1$ requests stream (Harbour) from both $i_{1,1}$ and $i_{2,1}$
- After 40 seconds, $c_2$ requests stream (News) from $i_{1,1}$

Rate-distortion Optimized Sharing
Mobility Results in Randomized Scenarios

- Average PSNR
  - Averaged over all clients and all streams

Parameter:
- 2-5 client peers
- 2 video sources
- 4 layers SVC with ca. 150kbit/sec
- Bandwidth limitation at servers: 200kbit/s
- Total 30 nodes active
- 650m x 650m area
- Mobility: Random movement, max. 3 m/s
- Stream duration 100s
- Average over 50 experiments

<table>
<thead>
<tr>
<th>Sequence:</th>
<th>City</th>
<th>Crew</th>
<th>News</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer:</td>
<td>Rate</td>
<td>PSNR</td>
<td>Rate</td>
</tr>
<tr>
<td>Base-layer</td>
<td>53.4</td>
<td>34.5</td>
<td>58.8</td>
</tr>
<tr>
<td>Enh.-layer 1</td>
<td>81.8</td>
<td>37.2</td>
<td>77.0</td>
</tr>
<tr>
<td>Enh.-layer 2</td>
<td>88.9</td>
<td>37.4</td>
<td>87.4</td>
</tr>
<tr>
<td>Enh.-layer 3</td>
<td>142.3</td>
<td>39.9</td>
<td>125.8</td>
</tr>
<tr>
<td>Enh.-layer 4</td>
<td>169.4</td>
<td>40.9</td>
<td>150.4</td>
</tr>
</tbody>
</table>

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Comments on Results

- Useful to allow overlay nodes to perform relatively simple optimization tasks
  - Especially when the network is heavily loaded

- Considerably more bandwidth efficient than the priority encoding (PET) approach
  - But naturally more susceptible to packet losses in base layer and loss of link to base-layer serving peer(s)
Thank you for your attention!

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