Performance Evaluation of Transport Protocols for Internet-Based Teleoperation Systems

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Introduction

- Teleoperation systems:
  - A human user manipulates tools stationed in a remote environment through an interactive communication medium
  - Military tasks, space robotics, underwater operations, and long distance medical diagnostics and surgeries

- Internet-based teleoperations systems:
  - A human operator sends motion/velocity data and receives reflecting force data from a teleoperator through the Internet
  - Availability, ease of access, and low cost
Introduction

- Internet-based teleoperation systems:
  - unknown and varying Internet delay may impair motion, velocity, and force data
  - data loss due to network congestion
  - Instability of the overall teleoperation system
Related work

- Control system approach:
  - Based on controller designs for stable operation between a human operator and a teleoperator in the case of constant delay

- Signal processing approach:
  - Based on prediction/estimation methods to compensate for varying delay and obtain original data

- Many other proposals also employ control system and signal processing approaches


Related work

- Transport protocol approach:
  - Only few approaches have been proposed
  - Modifications to existing protocols: TCP and UDP
    - Interactive real-time protocol (IRTP)
    - Real-time network protocol (RTNP)
    - Efficient transport protocol (ETP)


Existing protocols

- **Transport control protocol (TCP):**
  - reliable and connection-oriented
  - e-mail, web, remote terminal access, and file transfer
  - relatively large variations of delay
  - for teleoperations systems, it can be used for delivery of crucial information

- **User datagram protocol (UDP):**
  - unreliable and connectionless
  - streaming multimedia and voice over IP
  - small variations of delay
  - for teleoperation systems, it can be used for delivery of real-time data that is loss-tolerant

- **Real-time protocol (RTP):**
  - designed for multimedia services
  - employs an intermediate buffer, which may lead larger overall delay
  - not appropriate for teleoperation systems
Protocols for Internet-based teleoperation systems

- **Real-time network protocol (RTNP):**
  - the Internet delay depends not only on the network, but also on operating system
  - implemented based on UNIX environments
  - limitation: not available in other environments (Windows)

- **Interactive real-time protocol (IRTP):**
  - assigns priority in packets of real-time data
  - takes advantages of both TCP and UDP
    - TCP: crucial data transmission
    - UDP: real-time data transmission
Protocols for Internet-based teleoperation systems

- Efficient transport protocol (ETP):
  - based on inter-packet gap (IPG) implementation between packets
  - IPG may be controlled depending on network conditions
  - IPG control provides a congestion control in the network similar to TCP congestion control
  - IPG control with UDP is recommended

- IPG control:
  - adjusts time gap between successive data packets
  - when the network is congested, the IPG increases to reduce data rate within available bandwidth

<table>
<thead>
<tr>
<th>Packet #1</th>
<th>IPG</th>
<th>Packet #2</th>
<th>IPG</th>
<th>Packet #3</th>
</tr>
</thead>
</table>

IPG: Interpacket Gap

IPG between data packets
Simulation scenario

- Simulation tool: OPNET Modeler v. 14.5
- Simulation design:
  - WAN topology is designed with West and East subnets
    - human operator: located in the West subnet
    - teleoperator: located in the East subnet
  - Two subnets are connected via IP clouds:
    - packet discard ratio: 1 %
    - packet latency: 1 ms – 100 ms
  - Each subnet contains servers and LANs with star topology
  - Background traffic load is included
Simulation scenario: WAN topology

West subnet

East subnet

Backload
Simulation scenario: implementation

- TCP and UDP:
  - Using task configuration, 1 Mbps data rate is generated between a human operator and a teleoperator.

<table>
<thead>
<tr>
<th>Task attribute</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packet size</td>
<td>500 bytes</td>
</tr>
<tr>
<td>Inter-request time</td>
<td>8 ms</td>
</tr>
<tr>
<td>Packets per request</td>
<td>2</td>
</tr>
</tbody>
</table>

- TCP Reno or UDP is selected by application configuration.

- ETP (efficient transport protocol):
  - IPG (inter-packet gap) is implemented using task configuration.
  - Data rate is reduced depending on IPG values.

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<tr>
<td>IPG</td>
<td>1 ms – 8 ms</td>
</tr>
</tbody>
</table>
Simulation scenario: OPNET project view

- Protocols are selected using application configuration
Simulation scenario: OPNET process model view

- TCP and UDP process models

TCP

UDP
Simulation scenario: OPNET project view

- IPG values are defined using task configuration
Simulation results: TCP Reno

- End-to-end delay between a human operator and a teleoperator:
  - avg: 83.3 ms
  - min: 54.4 ms
  - max: 98.9 ms
  - std. dev: 8.4 ms

- Variations of the end-to-end delay are relatively large
Simulation results: UDP

- End-to-end delay between a human operator and a teleoperator:
  - avg: 101.9 ms
  - min: 93.9 ms
  - max: 107.6 ms
  - std. dev: 2.8 ms

- Compared with TCP, variations of the end-to-end delay are small
Simulation results: TCP with IPG

- IPG: 4 ms
- End-to-end delay:

<table>
<thead>
<tr>
<th>Delay</th>
<th>TCP Reno</th>
<th>TCP Reno with IPG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>83.3</td>
<td>81.4</td>
</tr>
<tr>
<td>Min.</td>
<td>54.4</td>
<td>25.3</td>
</tr>
<tr>
<td>Max.</td>
<td>98.9</td>
<td>105.9</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>8.4</td>
<td>11.3</td>
</tr>
</tbody>
</table>

- IPG does not improve the end-to-end delay performance with TCP

* IPG: inter-packet gap
Simulation results: UDP with IPG

- **IPG**: 1 ms
- **End-to-end delay**:

<table>
<thead>
<tr>
<th>Delay</th>
<th>UDP</th>
<th>IPG with UDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>101.9</td>
<td>95.7</td>
</tr>
<tr>
<td>Min.</td>
<td>93.9</td>
<td>89.5</td>
</tr>
<tr>
<td>Max.</td>
<td>107.6</td>
<td>103.2</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>2.8</td>
<td>2.3</td>
</tr>
</tbody>
</table>

- IPG improves the end-to-end delay performance with UDP

* IPG: inter-packet gap
Simulation results: UDP with large IPGs

- IPG: 1 ms – 8 ms
- End-to-end delay:

<table>
<thead>
<tr>
<th>Delay</th>
<th>UDP</th>
<th>IPG (1 ms)</th>
<th>IPG (2 ms)</th>
<th>IPG (4 ms)</th>
<th>IPG (8 ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>101.9</td>
<td>95.7</td>
<td>94.6</td>
<td>92.3</td>
<td>88.9</td>
</tr>
<tr>
<td>Min.</td>
<td>93.9</td>
<td>89.5</td>
<td>89.9</td>
<td>83.6</td>
<td>81.9</td>
</tr>
<tr>
<td>Max.</td>
<td>107.6</td>
<td>103.2</td>
<td>101.7</td>
<td>98.4</td>
<td>96.2</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>2.8</td>
<td>2.3</td>
<td>2.3</td>
<td>2.9</td>
<td>3.0</td>
</tr>
</tbody>
</table>

- End-to-end delay is reduced as IPG increases

* IPG: inter-packet gap
Simulation results: IPG should not be too large

- Increasing IPG gives larger variations of the end-to-end delay:

<table>
<thead>
<tr>
<th>Delay</th>
<th>IPG (1 ms)</th>
<th>IPG (32 ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg.</td>
<td>95.7</td>
<td>74.2</td>
</tr>
<tr>
<td>Min.</td>
<td>89.5</td>
<td>61.6</td>
</tr>
<tr>
<td>Max.</td>
<td>103.2</td>
<td>86.8</td>
</tr>
<tr>
<td>Std. dev.</td>
<td>2.3</td>
<td>5.6</td>
</tr>
</tbody>
</table>

- Optimal IPG value should be selected to avoid large variations

* IPG: inter-packet gap
Conclusions

- TCP and UDP were simulated for Internet-based teleoperation systems.
- ETP based on IPG values was evaluated and compared with existing protocols in terms of the end-to-end delay.
- TCP with IPG did not improve the end-to-end delay performance.
- UDP with IPG improved the end-to-end delay performance as IPG values increase.
- Optimal IPG value should be determined to:
  - avoid variations of the end-to-end delay
  - prevent discontinuity of haptic data in teleoperation systems:
    - motion data (human operator) > 30 Hz
    - force data (teleoperator) > 1,000 Hz

* IPG: inter-packet gap
* ETP: efficient transport protocol
References


Thank you