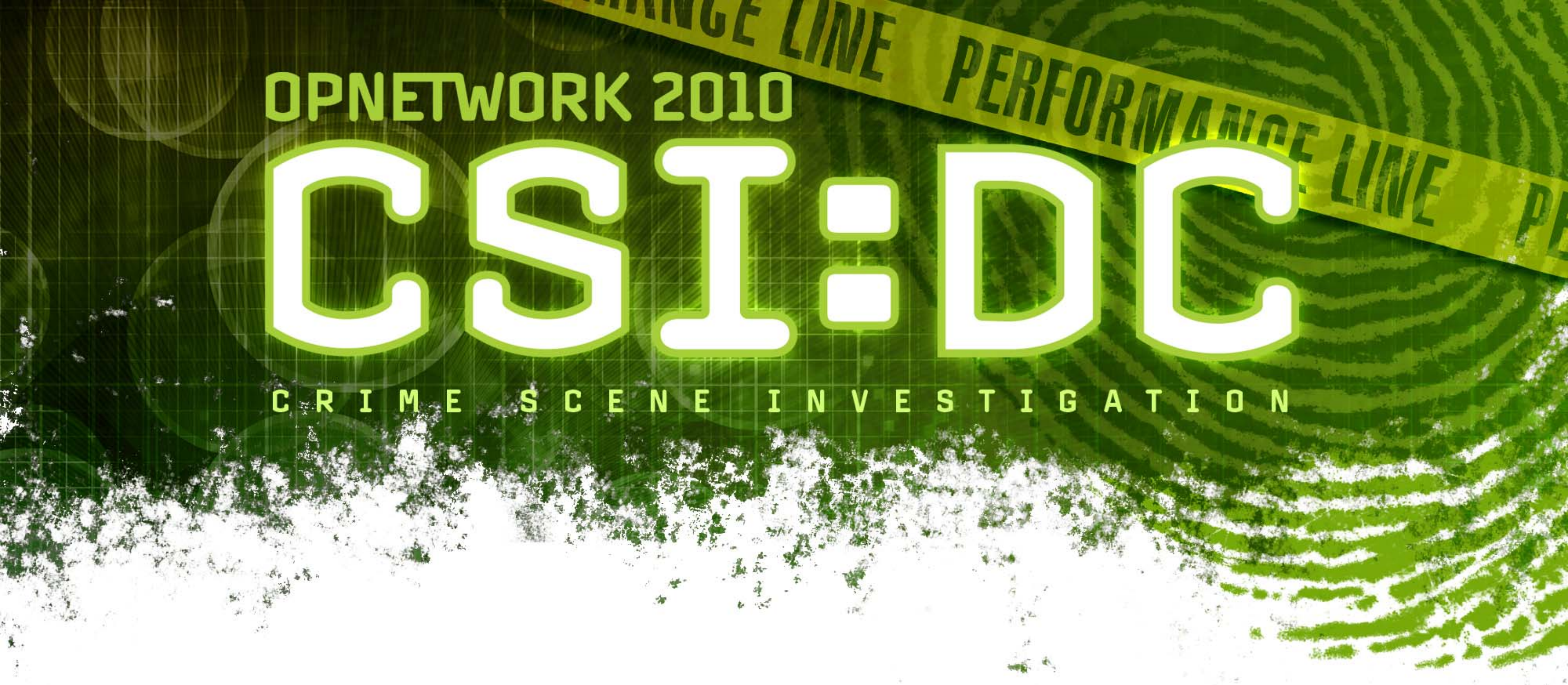
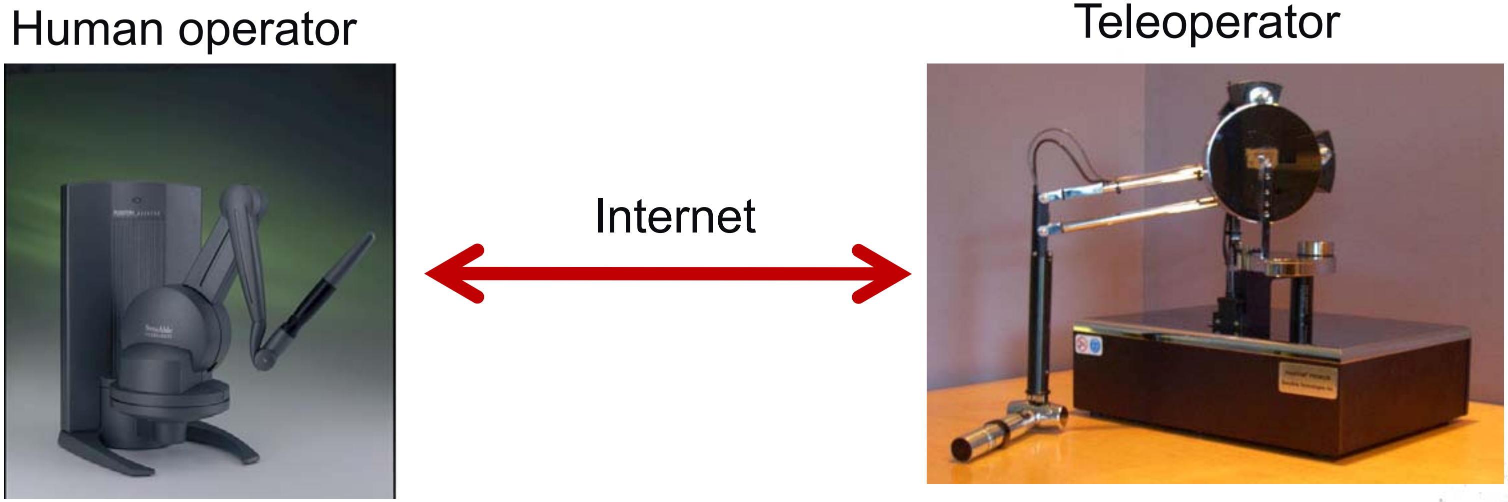


Performance Evaluation of Transport Protocols for Internet-Based Teleoperation Systems

J. Lee, S. Payandeh, and L. Trajković
Simon Fraser University

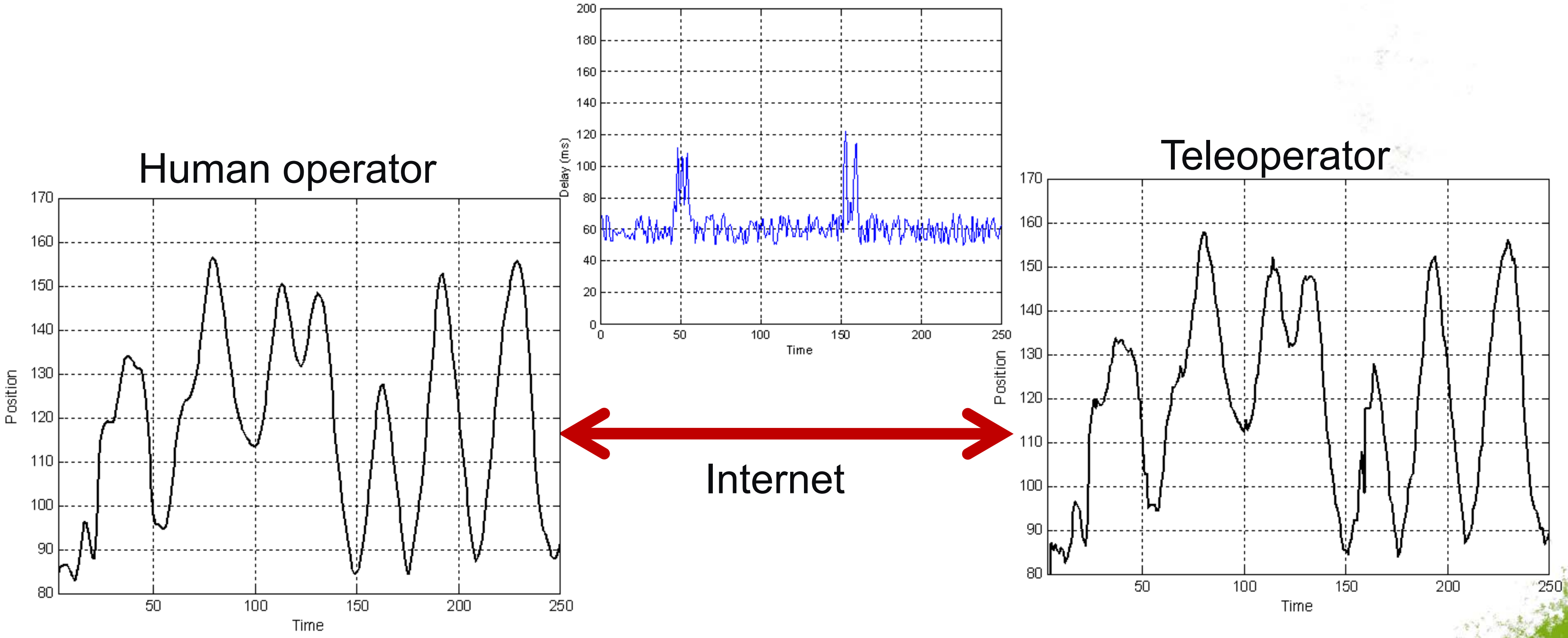
Introduction

- 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



Human operator

Internet

Teleoperator

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

G. Niemeyer and J. Slotine, "Designing force reflecting teleoperators with large time delays to appear as virtual tools," in *Proc. IEEE Int. Conf. on Robotics and Automation*, Albuquerque, NM, Apr. 1997, pp. 2212–2218.

K. Kawashima, K. Tadano, G. Sankaranarayana, and B. Hannaford, "Bilateral teleoperation with time delay using modified wave variables," in *Proc. IEEE Int. Conf. on Intelligent Robots and Systems*, Sept. 2008, pp. 424–429.

S. Clarke, G. Schillhuber, M. Zach, and H. Ulbrich, "The effects of simulated inertia and force prediction on delayed telepresence," *Presence*, vol. 16, no. 5, pp. 543–558, Oct. 2007.

J. Lee, S. Payandeh, and Lj. Trajković, "Application of prediction-based particle filters for teleoperations over the Internet," in *Proc. IASTED Int. Conf. on Robotics and Applications,* Cambridge, MA, USA, Nov. 2009, pp. 22–27.

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)

H. Schulzrinne, S. Deering, R. Frederick, and V. Jacobson, “RTP: a transport protocol for real-time applications,” *RFC 3550*, July 2003.

L. Ping, L. Wenjuan, and S. Zengqi, “Transport layer protocol reconfiguration for network-based robot control system,” in *Proc. IEEE Int. Conf. on Networking, Sensing, and Control*, Tucson, AZ, Mar. 2005, pp. 1049–1053.

Y. Uchimura and T. Yakoh, “Bilateral robot system on the real-time network structure,” *IEEE Trans. on Industrial Electronics*, vol. 51, no. 5, pp. 940–946, Oct. 2004.

R. Wirz, M. Ferre, R. Marín, J. Barrio, J. Claver, and J. Ortego, “Efficient transport protocol for networked haptics applications,” in *Proc. The 6th International Conference on Haptics: Perception, Devices and Scenarios*, Madrid, Spain, June 2008, vol. 5024, pp. 3–12.

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

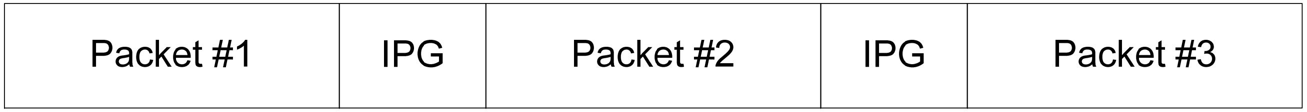
Protocols for Internet-based teleoperation systems

- 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



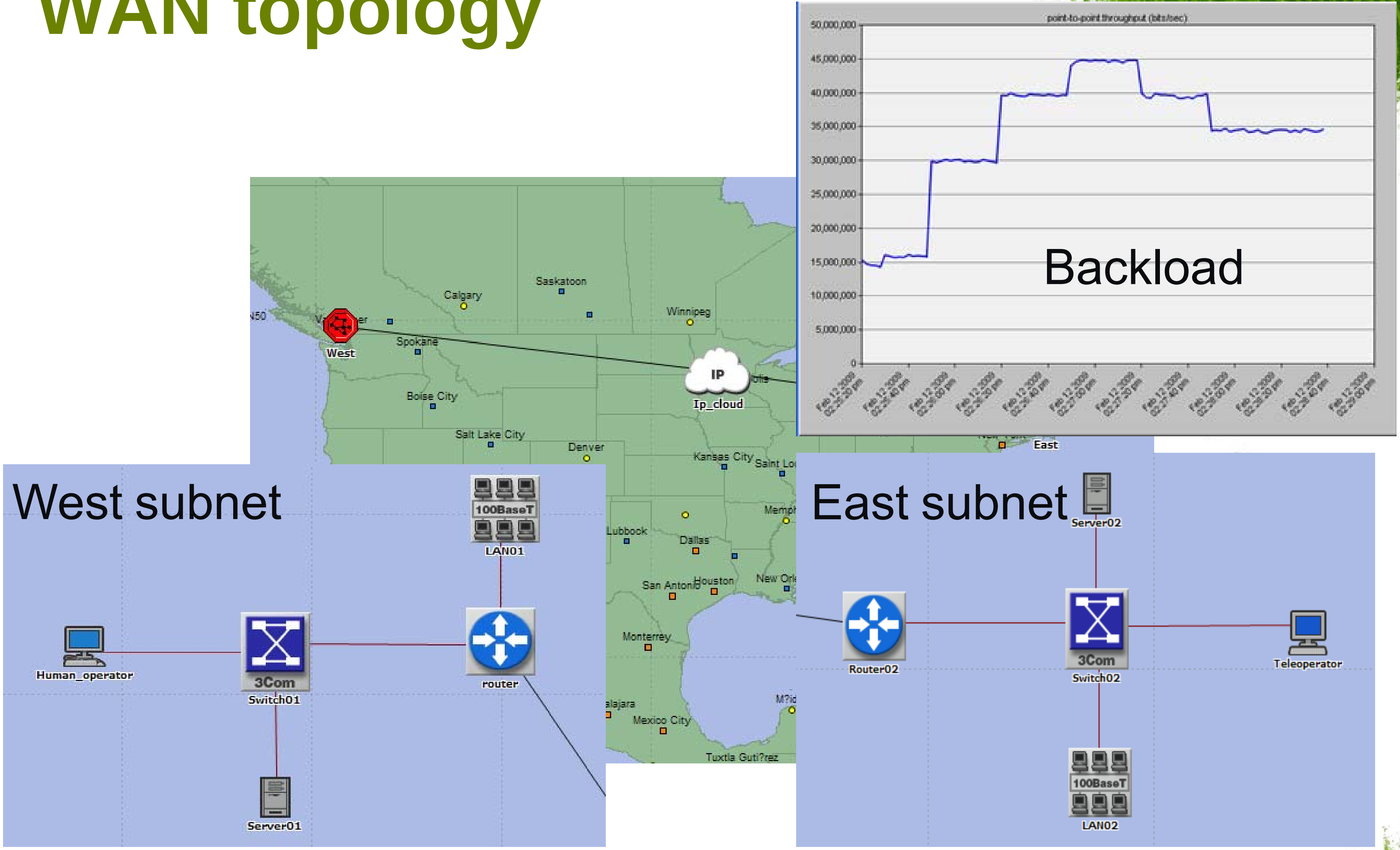
IPG: Interpacket Gap

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



Simulation scenario: implementation

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

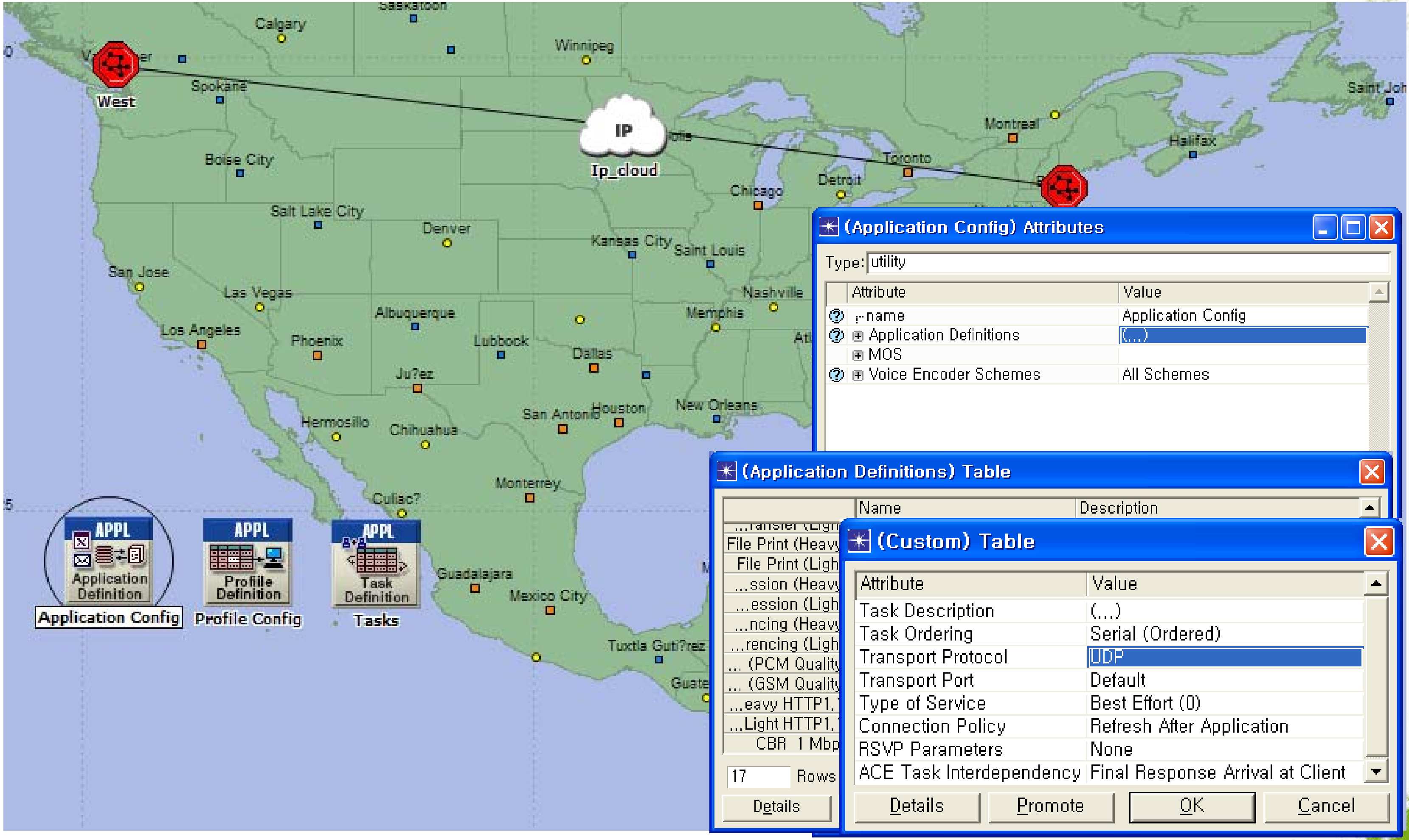
Task attribute	Parameters
Packet size	500 bytes
Inter-request time	8 ms
Packets per request	2

  - 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

Task attribute	Parameters
Packet size	500 bytes
Inter-request time	8 ms
Packets per request	2
IPG	1 ms – 8 ms

Simulation scenario: OPNET project view

- Protocols are selected using application configuration



(Application Config) Attributes

Type: utility

Attribute	Value
name	Application Config
⊞ Application Definitions	(...)
⊞ MOS	
⊞ Voice Encoder Schemes	All Schemes

(Application Definitions) Table

Name	Description
...ransfer (Ligh	
File Print (Heavy	
File Print (Ligh	
...ssion (Heavy	
...ession (Ligh	
...ncing (Heavy	
...rencing (Ligh	
... (PCM Quality	
... (GSM Quality	
...eavy HTTP1.	
...Light HTTP1.	
CBR 1 Mbp	

17 Rows

Details

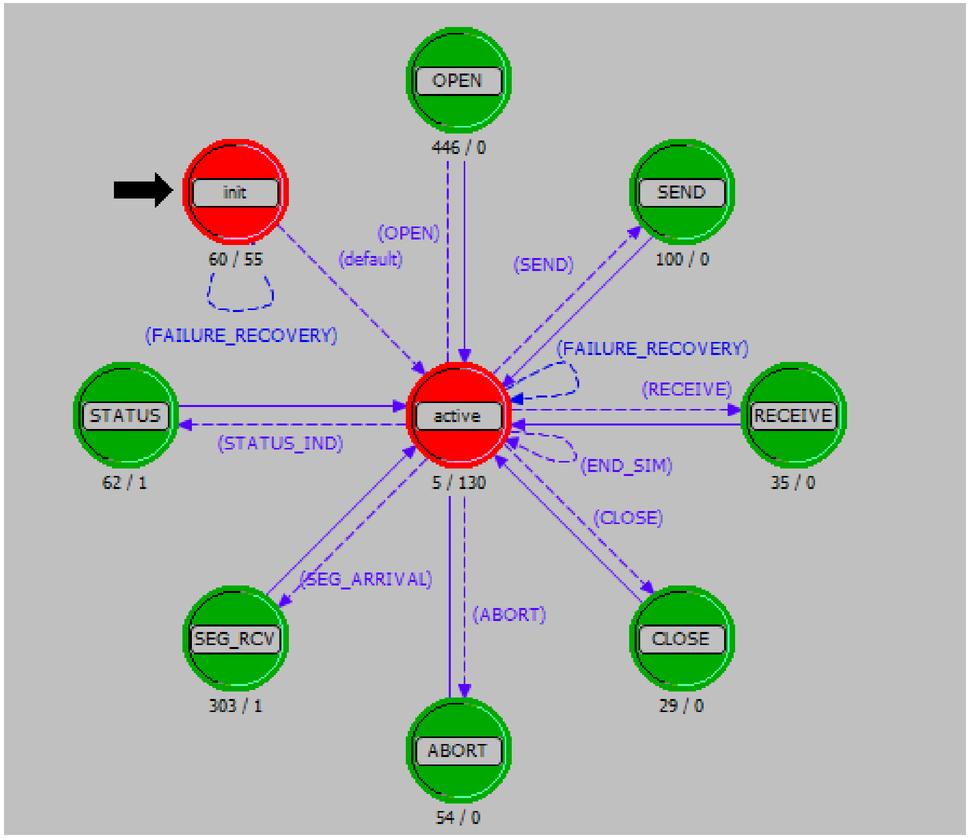
(Custom) Table

Attribute	Value
Task Description	(...)
Task Ordering	Serial (Ordered)
Transport Protocol	UDP
Transport Port	Default
Type of Service	Best Effort (0)
Connection Policy	Refresh After Application
RSVP Parameters	None
ACE Task Interdependency	Final Response Arrival at Client

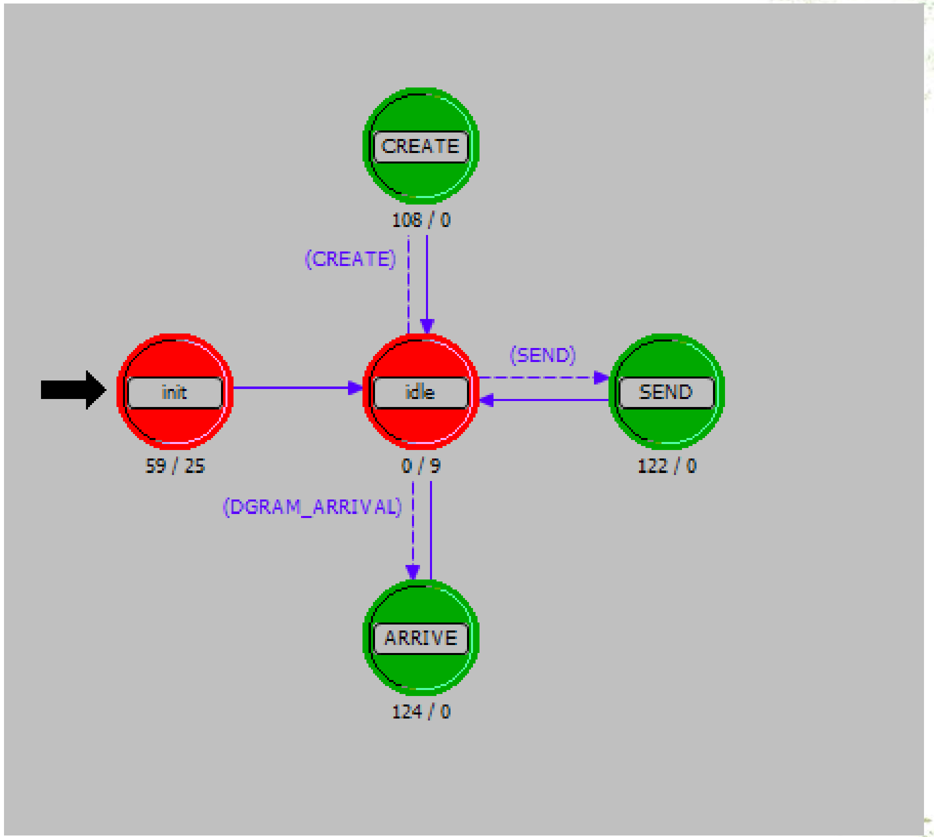
Details Promote OK Cancel

Simulation scenario: OPNET process model view

- TCP and UDP process models



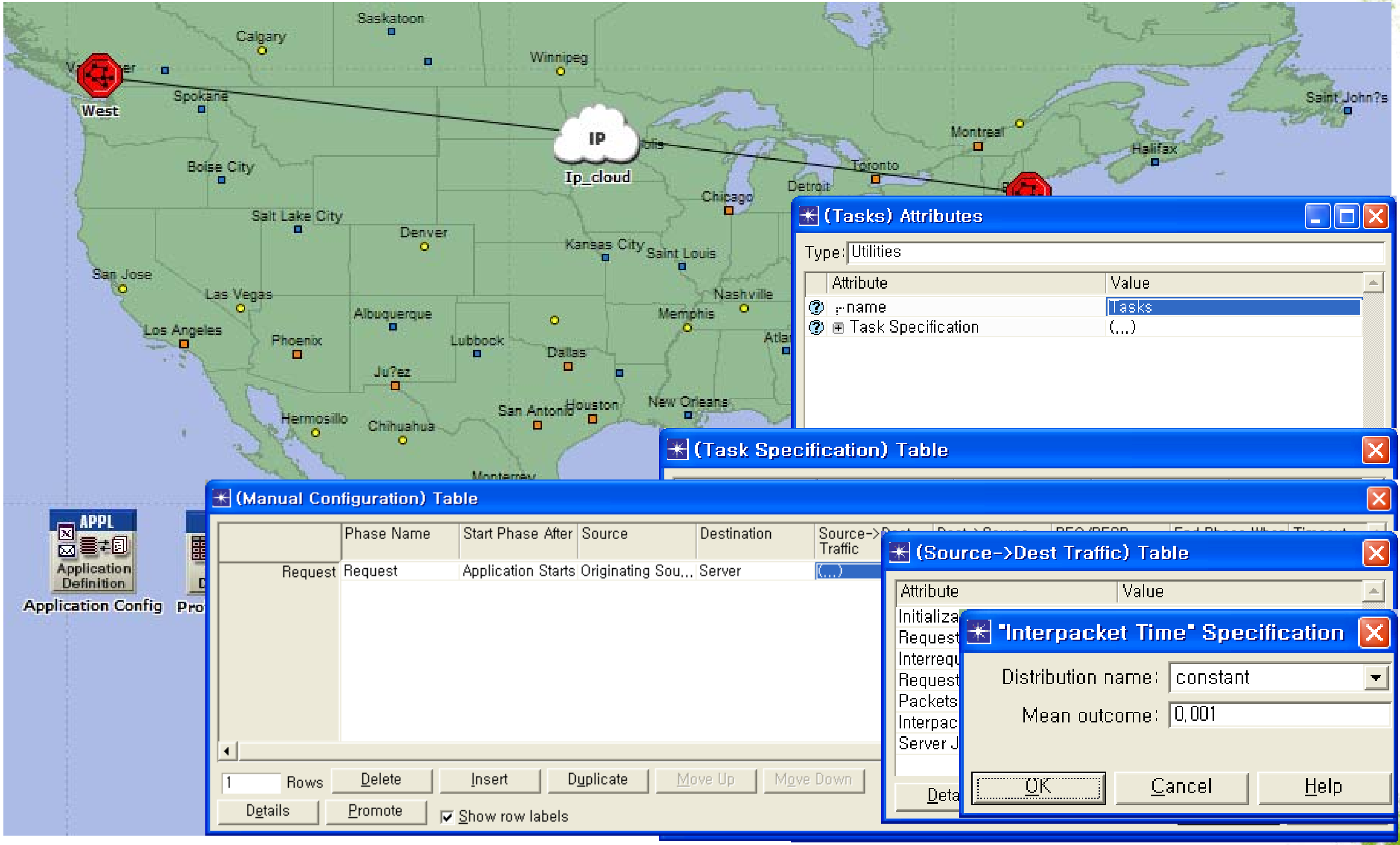
TCP



UDP

Simulation scenario: OPNET project view

- IPG values are defined using task configuration



(Tasks) Attributes

Type: Utilities

Attribute	Value
name	Tasks
⊞ Task Specification	(...)

(Task Specification) Table

(Manual Configuration) Table

	Phase Name	Start Phase After	Source	Destination	Source->Dest Traffic
Request	Request	Application Starts	Originating Sou...	Server	(...)

1 Rows | Delete | Insert | Duplicate | Move Up | Move Down

Details | Promote | ☑ Show row labels

(Source->Dest Traffic) Table

Attribute	Value
Initializa	
Request	
Interrequ	
Request	
Packets	
Interpac	
Server J	

Deta

"Interpacket Time" Specification

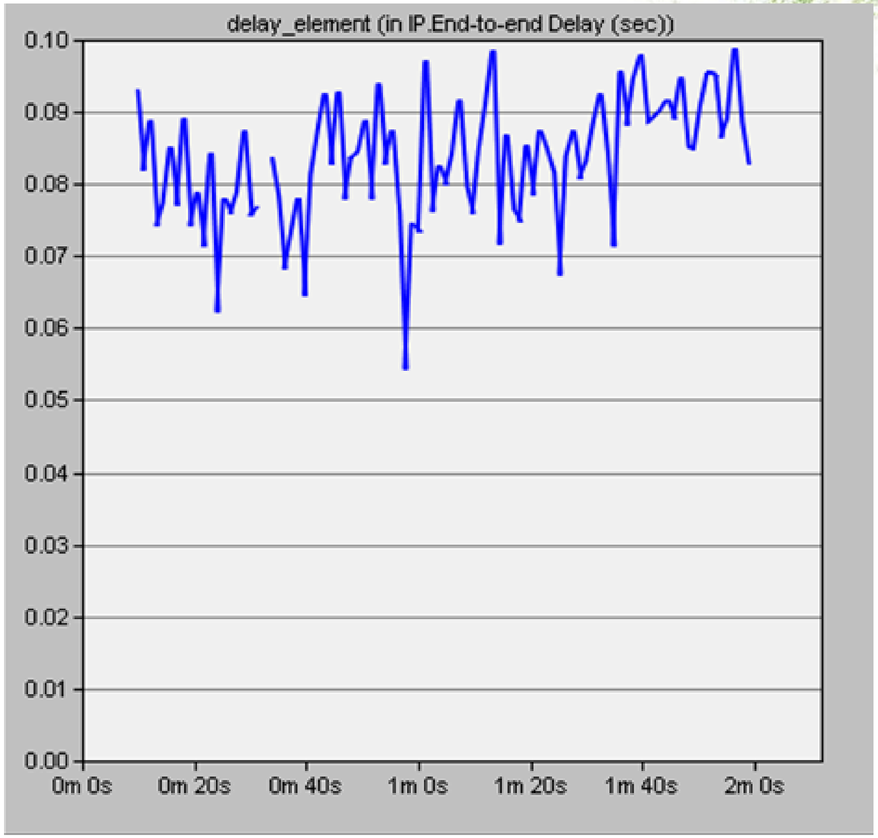
Distribution name: constant

Mean outcome: 0,001

OK | Cancel | Help

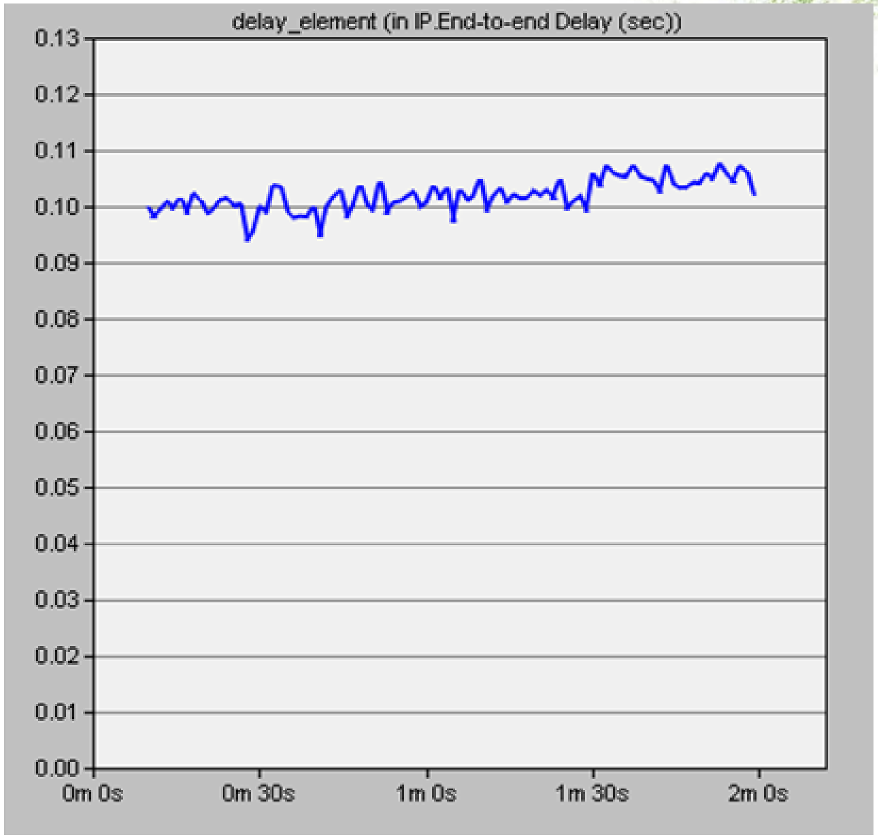
Simulation results: TCP Reno

- 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

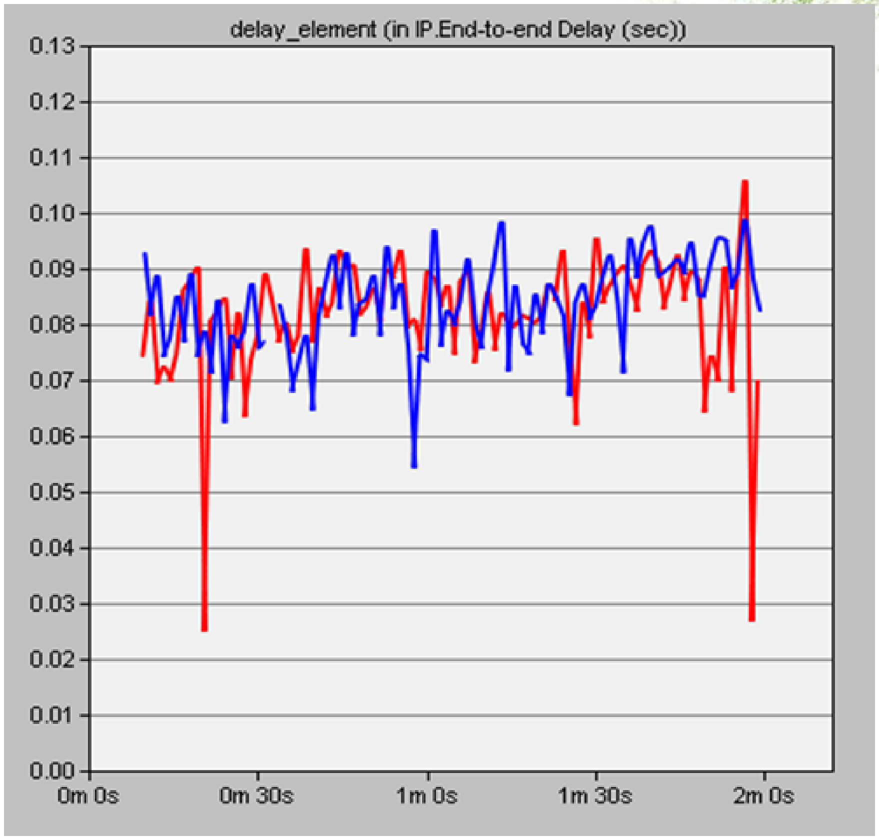


Simulation results: TCP with IPG

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

Delay	TCP Reno	TCP Reno with IPG
Avg.	83.3	81.4
Min.	54.4	25.3
Max.	98.9	105.9
Std. dev.	8.4	11.3

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



🟦 TCP Reno
🟥 TCP Reno with IPG

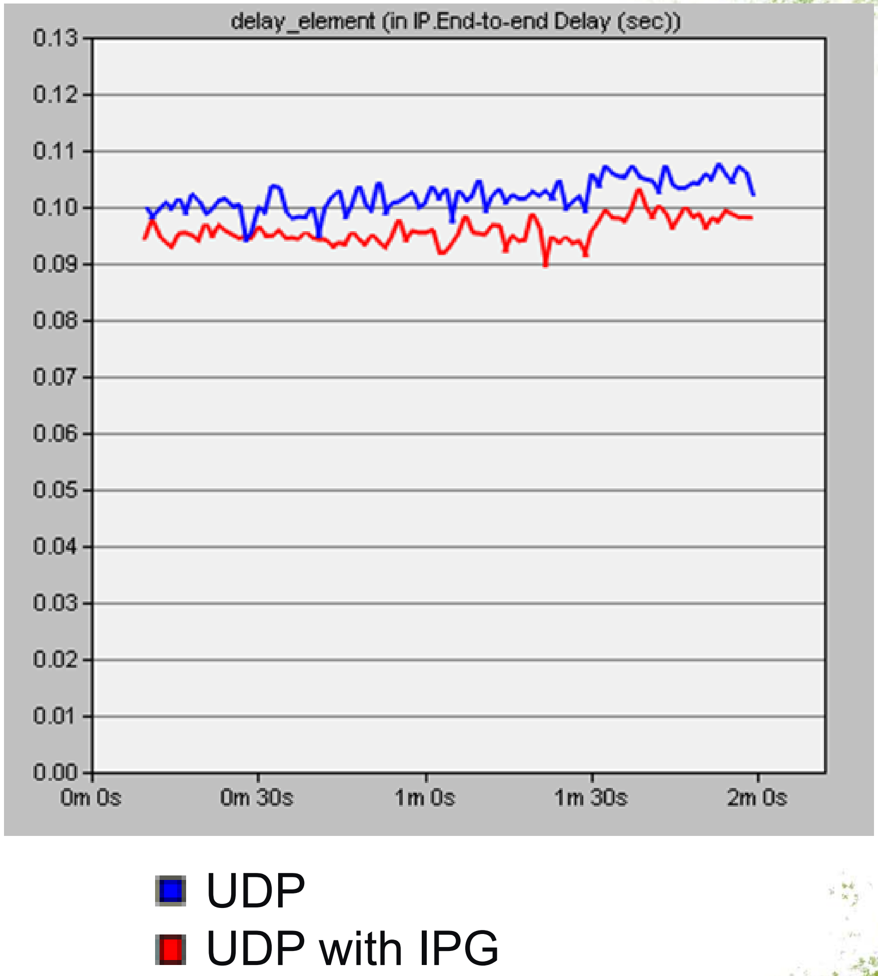
* IPG: inter-packet gap

Simulation results: UDP with IPG

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

Delay	UDP	IPG with UDP
Avg.	101.9	95.7
Min.	93.9	89.5
Max.	107.6	103.2
Std. dev.	2.8	2.3

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

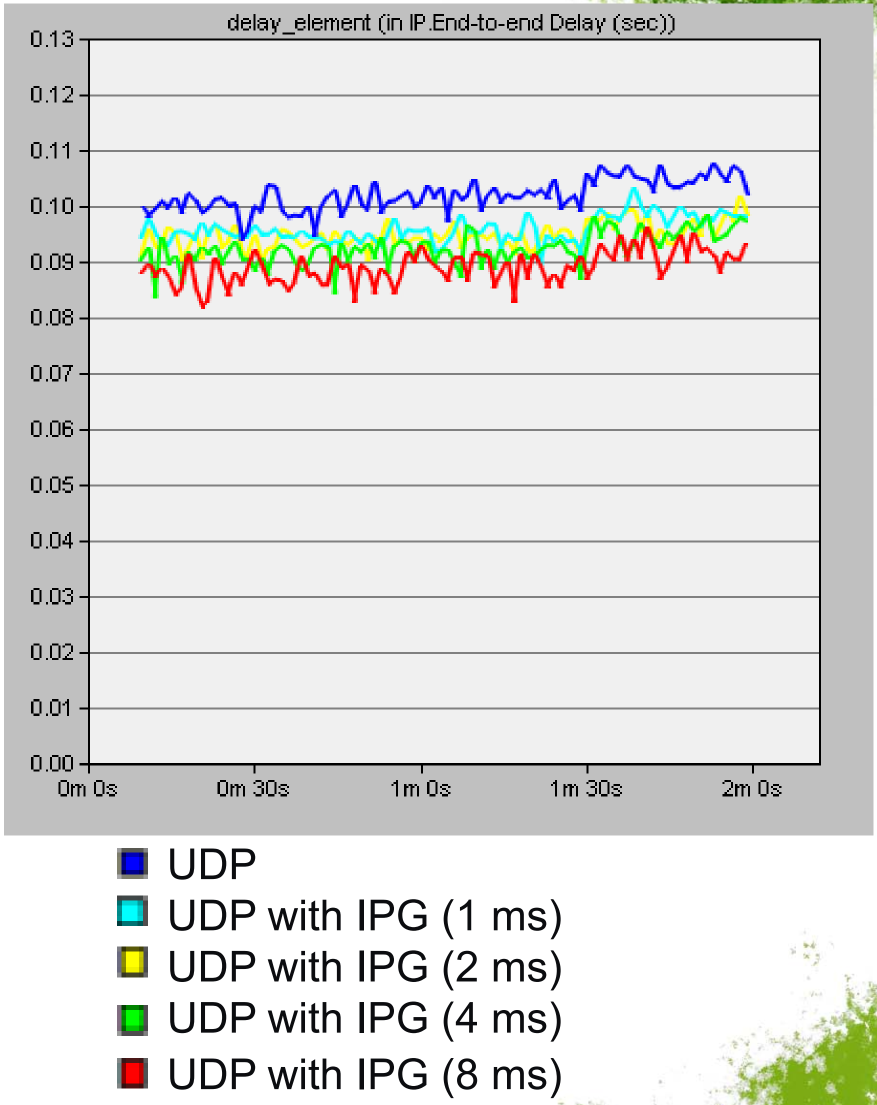


* IPG: inter-packet gap

Simulation results: UDP with large IPGs

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

Delay	**UDP**	**IPG (1 ms)**	**IPG (2 ms)**	**IPG (4 ms)**	**IPG (8 ms)**
Avg.	101.9	95.7	94.6	92.3	88.9
Min.	93.9	89.5	89.9	83.6	81.9
Max.	107.6	103.2	101.7	98.4	96.2
Std. dev.	2.8	2.3	2.3	2.9	3.0



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

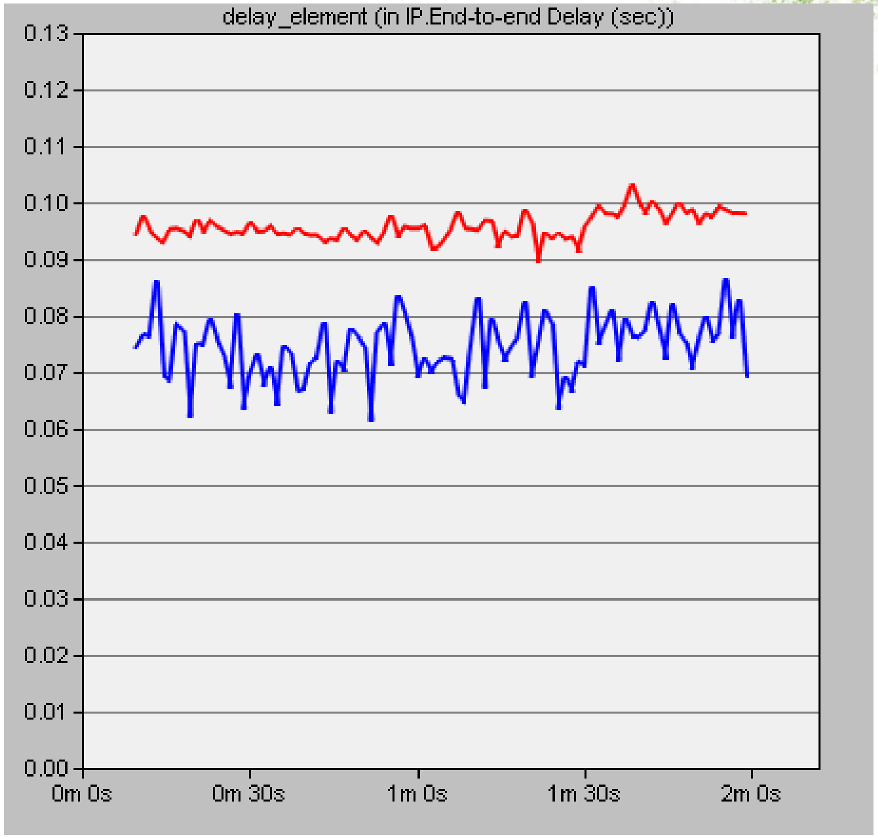
* IPG: inter-packet gap

Simulation results: IPG should not be too large

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

Delay	IPG (1 ms)	IPG (32 ms)
Avg.	95.7	74.2
Min.	89.5	61.6
Max.	103.2	86.8
Std. dev.	2.3	5.6

- Optimal IPG value should be selected to avoid large variations



🟥 UDP with IPG (1 ms)
🟦 UDP with IPG (32 ms)

* 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

[1] E. Kamrani, H. Momeni, and A. Sharafat, “Modeling Internet delay dynamics for teleoperation,” in *Proc. IEEE Int. Conf. on Control Applications*, Aug. 2005, pp. 1528–1533.

[2] G. Niemeyer and J. Slotine, “Stable adaptive teleoperation,” *IEEE Journal of Oceanic Engineering*, vol. 16, no. 1, pp. 152–162, Jan. 1991.

[3] G. Niemeyer and J. Slotine, “Designing force reflecting teleoperators with large time delays to appear as virtual tools,” in *Proc. IEEE Int. Conf. on Robotics and Automation*, Albuquerque, NM, Apr. 1997, pp. 2212–2218.

[4] K. Kawashima, K. Tadano, G. Sankaranarayana, and B. Hannaford, “Bilateral teleoperation with time delay using modified wave variables,” in *Proc. IEEE Int. Conf. on Intelligent Robots and Systems*, Sept. 2008, pp. 424–429.

[5] S. Clarke, G. Schillhuber, M. Zach, and H. Ulbrich, “The effects of simulated inertia and force prediction on delayed telepresence,” *Presence*, vol. 16, no. 5, pp. 543–558, Oct. 2007.

[6] S. Munir and W. Book, “Internet-based teleoperation using wave variables with prediction,” *IEEE/ASME Trans. on Mechatronics*, vol. 7, no 2, pp. 124–133, June 2002.

[7] J. Lee, S. Payandeh, and Lj. Trajković, “Application of prediction-based particle filters for teleoperations over the Internet,” in *Proc. The 14th IASTED Int. Conf. on Robotics and Applications, RA 2009*, Cambridge, MA, USA, Nov. 2009, pp. 22–27.

[8] H. Schulzrinne, S. Deering, R. Frederick, and V. Jacobson, “RTP: a transport protocol for real-time applications,” *RFC 3550*, July 2003.

[9] L. Ping, L. Wenjuan, and S. Zengqi, “Transport layer protocol reconfiguration for network-based robot control system,” in *Proc. IEEE Int. Conf. on Networking, Sensing, and Control*, Tucson, AZ, Mar. 2005, pp. 1049–1053.

[10] Y. Uchimura and T. Yakoh, “Bilateral robot system on the real-time network structure,” *IEEE Trans. on Industrial Electronics*, vol. 51, no. 5, pp. 940–946, Oct. 2004.

[11] R. Rejaie, M. Handley, and D. Estrin, “RAP: An end-to-end rate-based congestion control mechanism for realtime streams in the Internet,” in *Proc. IEEE INFOCOM*, Mar. 1999, pp. 1337–1345.

[12] R. Wirz, M. Ferre, R. Marín, J. Barrio, J. Claver, and J. Ortego, “Efficient transport protocol for networked haptics applications,” in *Proc. The 6th International Conference on Haptics: Perception, Devices and Scenarios*, Madrid, Spain, June 2008, vol. 5024, pp. 3–12.

Thank you