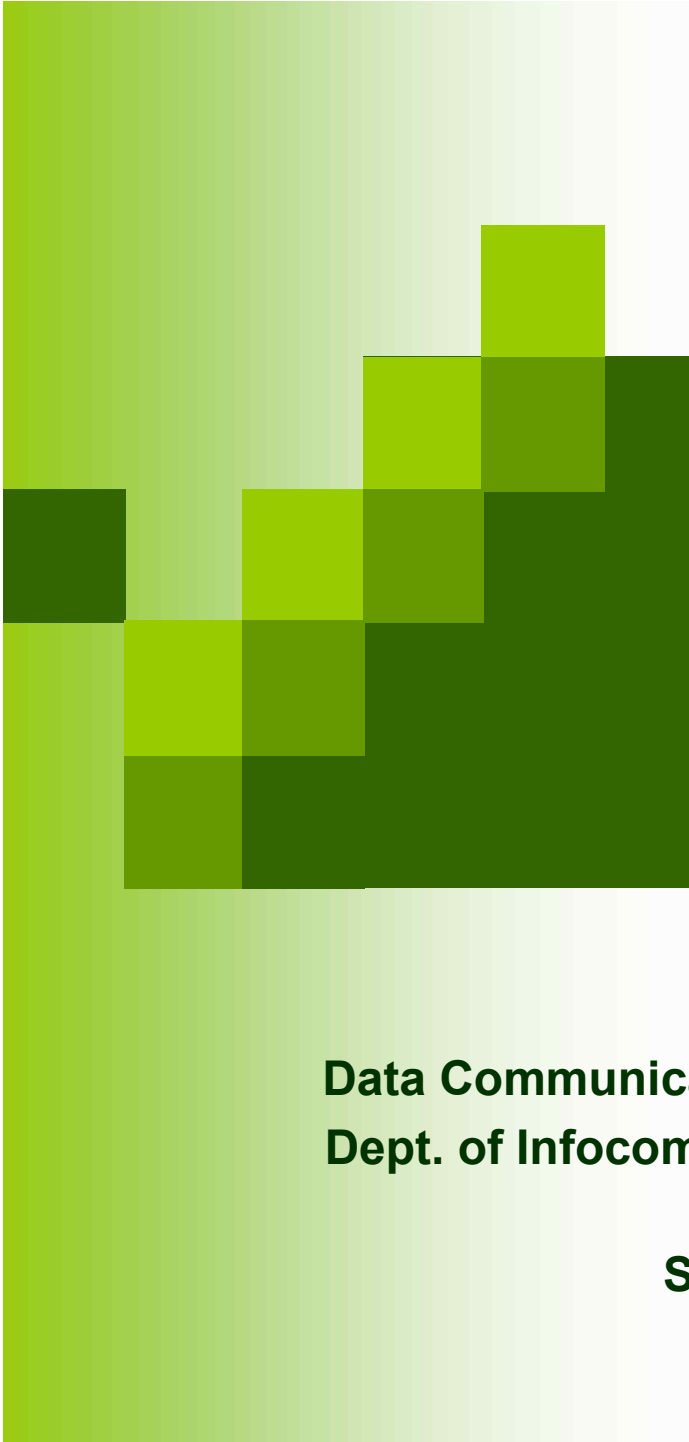




A Network Emulator on the NetFPGA Platform

1st ASIA NetFPGA Developer's Wrokshop
2010. 6. 14

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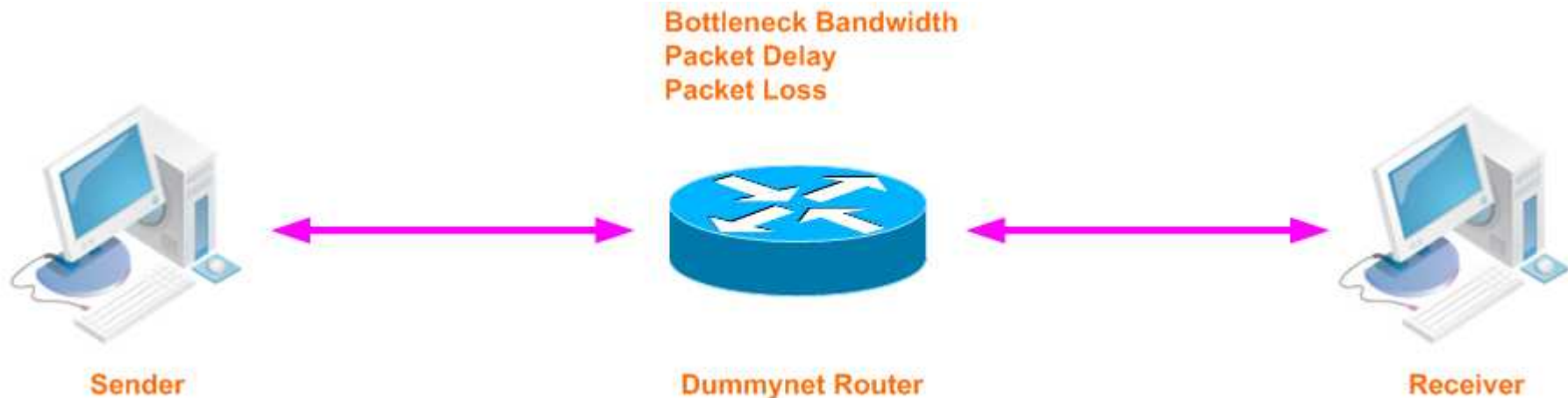
- ❖ Introduction to Network Emulation
- ❖ A network emulator on the NetFPGA platform
- ❖ Performance Evaluations
- ❖ Demonstrations
- ❖ References



Network Emulation

❖ Network Emulation is

- a technique where the properties of an existing, planned network are simulated in order to access performance, predict the impact of change, or otherwise optimize technology decision making.





Widely Used Network Emulators

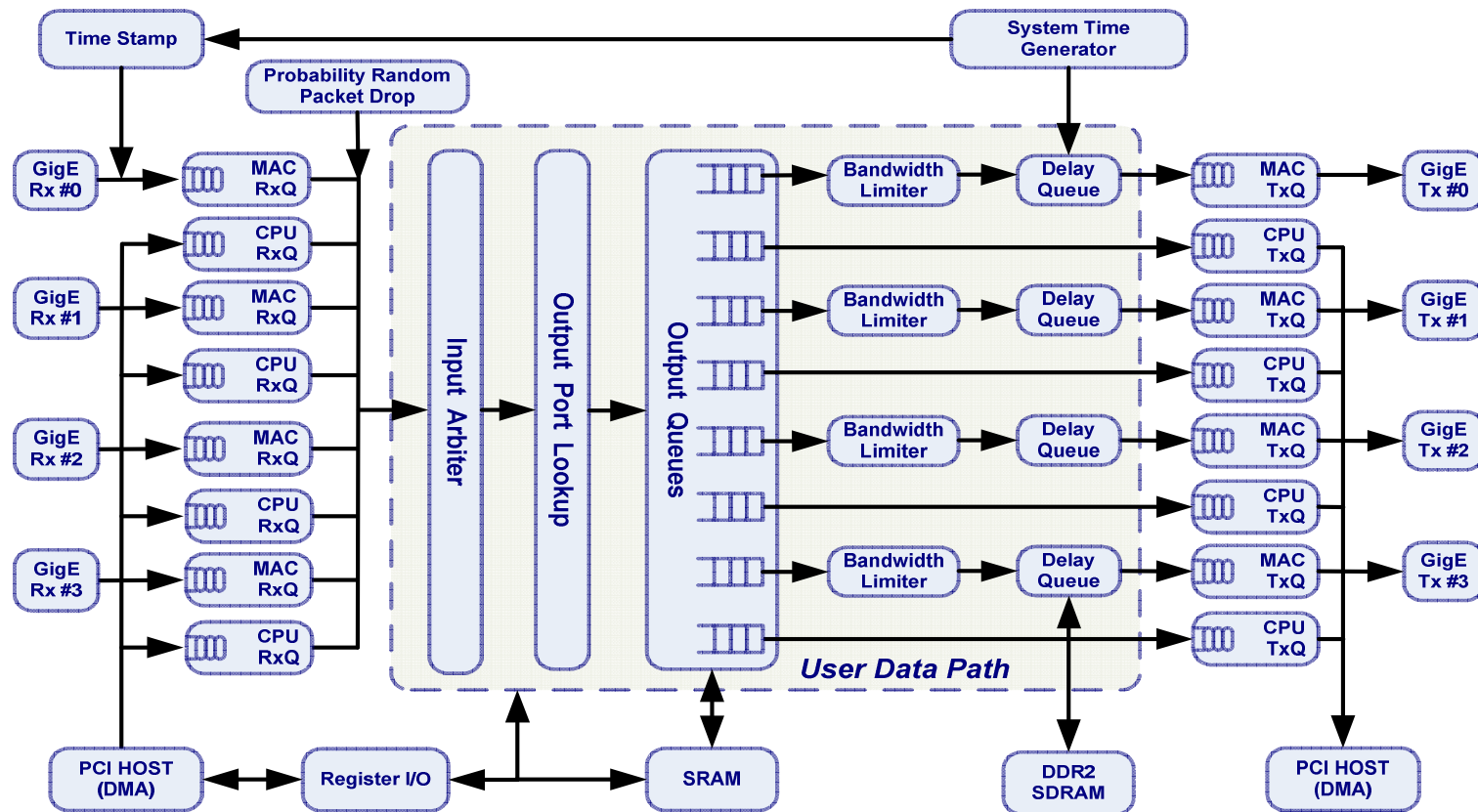
❖ Dummynet & NISTnet

- Software-based network emulator
 - ❑ software packages running on PC
- bottleneck bandwidth
 - ❑ bps ~ 1Gbps
- probability random packet loss
 - ❑ 0~1 (floating point number)
- packet delay
 - ❑ ms



NetFPGA Network Emulator

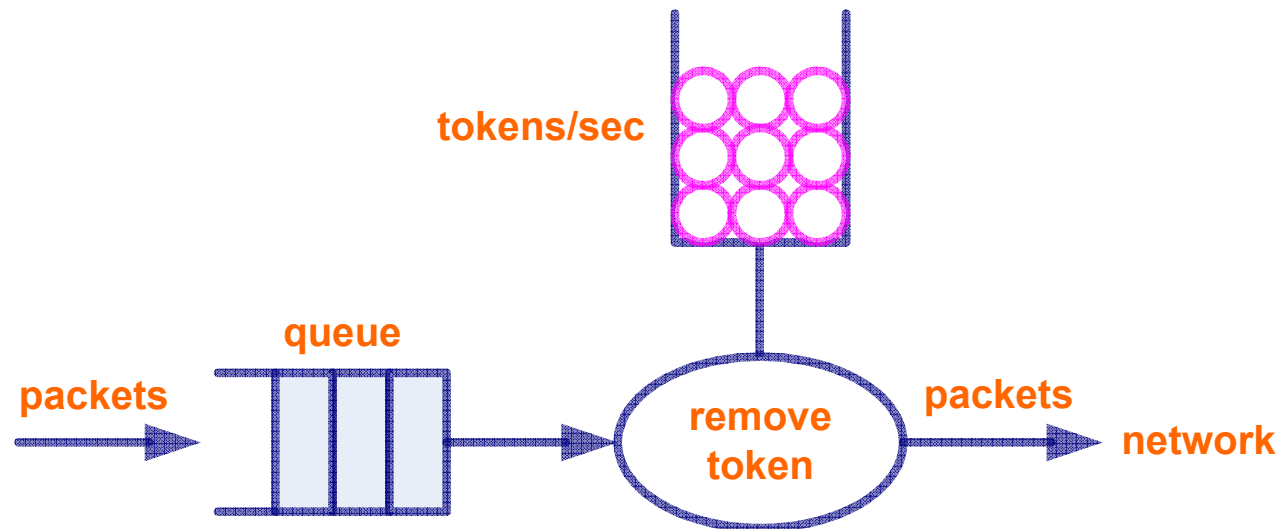
❖ Overall Pipeline Architecture and features



NetFPGA Network Emulator (cont'd)

❖ Bandwidth Limiter Module

- Traffic shapping with token bucket
- Bottleneck bandwidth
 - ❑ 0 ~ 1Gbps



NetFPGA Network Emulator (cont'd)

❖ Packet Delay Module

- Time stamping for each ingress packet
- Packet delay
 - ❑ 0ns ~ ($2^{32} - 1$)ns (8ns step, 125MHz)

latency of packet
 10ms = (0xe18 – 0x936) x 8ns

➤ Ingress packet



➤ Outgoing packet



NetFPGA Network Emulator (cont'd)

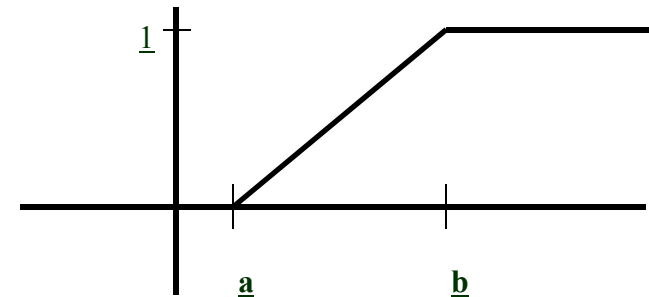
❖ Packet Drop Module

- PRNG with 21-bits LFSR
- Generation Polynomial of LFSR

$$P(x) = x^{21} + x^{20} + x + 1$$

- Expectation and CDF of a Uniform Random Variable

$$E[X] = \int_{\alpha}^{\beta} x \frac{1}{\beta - \alpha} dx = \frac{\beta + \alpha}{2}$$



- Probability Random Packet Loss
 - 0.001% ~ 100%

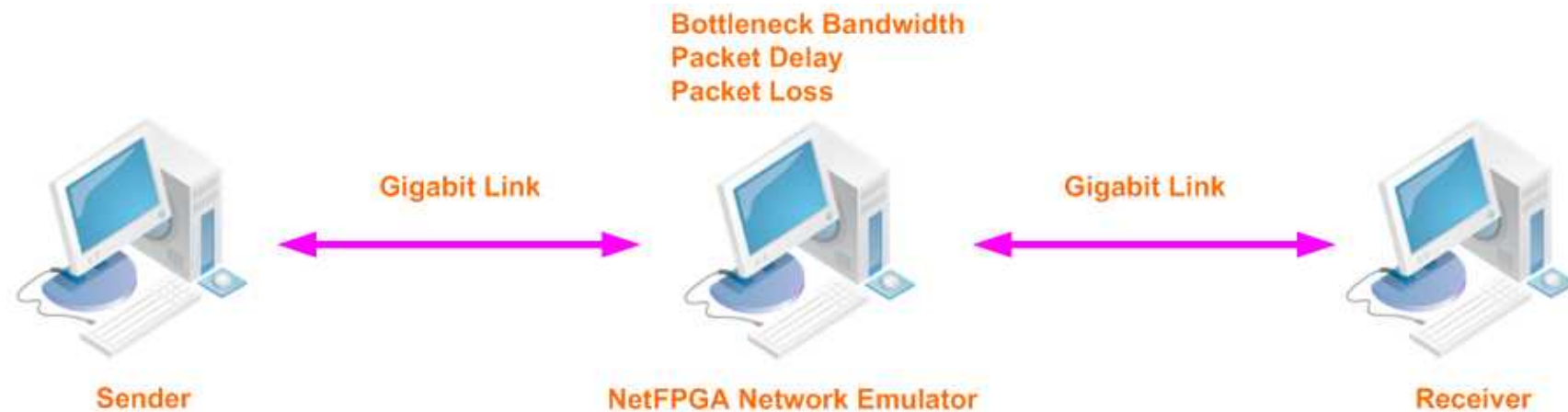
Experimental Setup

❖ Dummynet PC

- OS: FreeBSD 8.0
- CPU: Intel Quad-Core i5, 2.8 GHz
- Memory: 4 Gbytes
- NIC: Gigabit Ethernet

❖ Sender, Receiver and NetFPGA PCs

- OS: CentOS 5.2
- CPU: Intel Dual-Core E8400, 3.0GHz
- Memory: 4 Gbytes
- NIC: Gigabit Ethernet



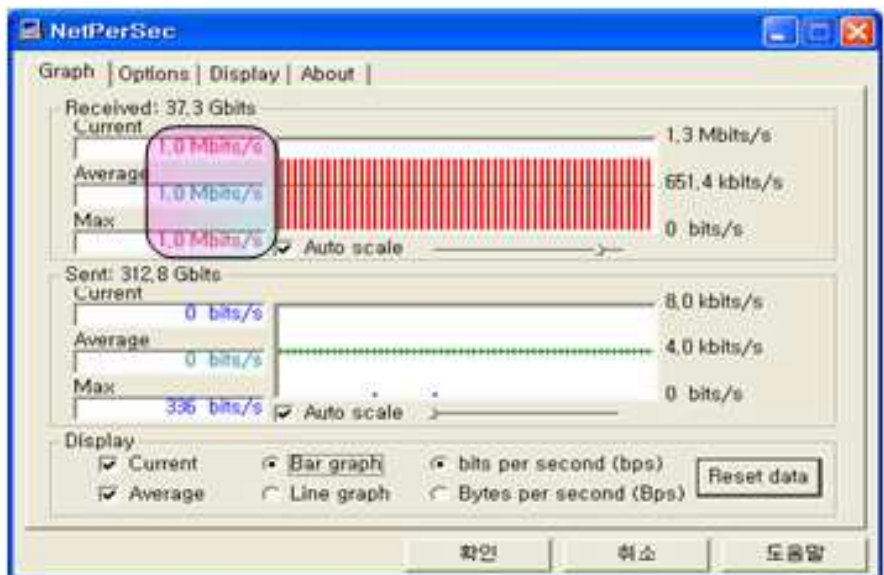


Experimental Results

❖ Bottleneck bandwidth & Delay

```
명령 프롬프트 - hrping.exe 192.168.0.1 -n 1000 -s 100 -o
Reply from 192.168.0.1: seq=001e time=0.201ms TTL=64 ID=4801
Reply from 192.168.0.1: seq=001f time=0.136ms TTL=64 ID=4802
Reply from 192.168.0.1: seq=0020 time=0.187ms TTL=64 ID=4803
Reply from 192.168.0.1: seq=0021 time=0.128ms TTL=64 ID=4804
Reply from 192.168.0.1: seq=0022 time=0.180ms TTL=64 ID=4805
Reply from 192.168.0.1: seq=0023 time=0.125ms TTL=64 ID=4806
Reply from 192.168.0.1: seq=0024 time=0.200ms TTL=64 ID=4807
Reply from 192.168.0.1: seq=0025 time=0.185ms TTL=64 ID=4808
Reply from 192.168.0.1: seq=0026 time=0.190ms TTL=64 ID=4809
Reply from 192.168.0.1: seq=0027 time=0.208ms TTL=64 ID=480a
Reply from 192.168.0.1: seq=0028 time=0.184ms TTL=64 ID=480b
Reply from 192.168.0.1: seq=0029 time=0.127ms TTL=64 ID=480c
Reply from 192.168.0.1: seq=002a time=0.180ms TTL=64 ID=480d
Reply from 192.168.0.1: seq=002b time=0.127ms TTL=64 ID=480e
Reply from 192.168.0.1: seq=002c time=0.187ms TTL=64 ID=480f
Reply from 192.168.0.1: seq=002d time=0.184ms TTL=64 ID=4810
Reply from 192.168.0.1: seq=002e time=0.182ms TTL=64 ID=4811
Reply from 192.168.0.1: seq=002f time=100.197ms TTL=64 ID=4812
Reply from 192.168.0.1: seq=0030 time=100.212ms TTL=64 ID=4813
Reply from 192.168.0.1: seq=0031 time=100.192ms TTL=64 ID=4814
Reply from 192.168.0.1: seq=0032 time=100.175ms TTL=64 ID=4815
Reply from 192.168.0.1: seq=0033 time=100.198ms TTL=64 ID=4816
Reply from 192.168.0.1: seq=0034 time=100.201ms TTL=64 ID=4817
Reply from 192.168.0.1: seq=0035 time=100.213ms TTL=64 ID=4818
Reply from 192.168.0.1: seq=0036 time=100.155ms TTL=64 ID=4819
Reply from 192.168.0.1: seq=0037 time=100.190ms TTL=64 ID=481a
Reply from 192.168.0.1: seq=0038 time=100.201ms TTL=64 ID=481b
Reply from 192.168.0.1: seq=0039 time=100.216ms TTL=64 ID=481c
Reply from 192.168.0.1: seq=003a time=100.204ms TTL=64 ID=481d
Reply from 192.168.0.1: seq=003b time=100.191ms TTL=64 ID=481e
Reply from 192.168.0.1: seq=003c time=100.192ms TTL=64 ID=481f
Reply from 192.168.0.1: seq=003d time=100.189ms TTL=64 ID=4820
Reply from 192.168.0.1: seq=003e time=100.221ms TTL=64 ID=4821
Reply from 192.168.0.1: seq=003f time=100.206ms TTL=64 ID=4822
Reply from 192.168.0.1: seq=0040 time=100.221ms TTL=64 ID=4823
Reply from 192.168.0.1: seq=0041 time=100.145ms TTL=64 ID=4824
Reply from 192.168.0.1: seq=0042 time=100.207ms TTL=64 ID=4825
Reply from 192.168.0.1: seq=0043 time=100.197ms TTL=64 ID=4826
Reply from 192.168.0.1: seq=0044 time=100.208ms TTL=64 ID=4827
Reply from 192.168.0.1: seq=0045 time=100.183ms TTL=64 ID=4828
Reply from 192.168.0.1: seq=0046 time=100.219ms TTL=64 ID=4829
Reply from 192.168.0.1: seq=0047 time=100.192ms TTL=64 ID=482a
Reply from 192.168.0.1: seq=0048 time=100.207ms TTL=64 ID=482b
Reply from 192.168.0.1: seq=0049 time=100.188ms TTL=64 ID=482c
Reply from 192.168.0.1: seq=004a time=100.186ms TTL=64 ID=482d
```

[ID]	Interval	Transfer	Bandwidth	Jitter	Lost/Total	Datagrams
[1928]	1180.0-1181.0	sec 123 KB	tes 1.01 Mbits/sec	8.318 ms	3154/ 3240	<97%>
[1928]	1181.0-1182.0	sec 123 KB	tes 1.01 Mbits/sec	7.302 ms	3069/ 3155	<97%>
[1928]	1182.0-1183.0	sec 123 KB	tes 1.01 Mbits/sec	10.041 ms	3798/ 3884	<98%>
[1928]	1183.0-1184.0	sec 122 KB	tes 1000 Kbits/sec	8.415 ms	3121/ 3206	<97%>
[1928]	1184.0-1185.0	sec 123 KB	tes 1.01 Mbits/sec	10.037 ms	3061/ 3147	<97%>
[1928]	1185.0-1186.0	sec 123 KB	tes 1.01 Mbits/sec	7.475 ms	3148/ 3234	<97%>
[1928]	1186.0-1187.0	sec 123 KB	tes 1.01 Mbits/sec	8.308 ms	3134/ 3220	<97%>
[1928]	1187.0-1188.0	sec 123 KB	tes 1.01 Mbits/sec	8.951 ms	3948/ 4034	<98%>
[1928]	1188.0-1189.0	sec 123 KB	tes 1.01 Mbits/sec	6.311 ms	3116/ 3202	<97%>
[1928]	1189.0-1190.0	sec 123 KB	tes 1.01 Mbits/sec	7.915 ms	3159/ 3245	<97%>
[1928]	1190.0-1191.0	sec 123 KB	tes 1.01 Mbits/sec	9.886 ms	3112/ 3198	<97%>
[1928]	1191.0-1192.0	sec 123 KB	tes 1.01 Mbits/sec	6.733 ms	3121/ 3207	<97%>
[1928]	1192.0-1193.0	sec 122 KB	tes 1000 Kbits/sec	8.617 ms	3593/ 3678	<98%>
[1928]	1193.0-1194.0	sec 123 KB	tes 1.01 Mbits/sec	8.640 ms	3122/ 3208	<97%>
[1928]	1194.0-1195.0	sec 123 KB	tes 1.01 Mbits/sec	8.540 ms	3158/ 3244	<97%>
[1928]	1195.0-1196.0	sec 123 KB	tes 1.01 Mbits/sec	8.168 ms	3117/ 3203	<97%>
[1928]	1196.0-1197.0	sec 123 KB	tes 1.01 Mbits/sec	7.141 ms	3147/ 3233	<97%>
[1928]	1197.0-1198.0	sec 123 KB	tes 1.01 Mbits/sec	6.259 ms	3440/ 3526	<98%>
[1928]	1198.0-1199.0	sec 123 KB	tes 1.01 Mbits/sec	7.914 ms	3162/ 3248	<97%>
[1928]	1199.0-1200.0	sec 123 KB	tes 1.01 Mbits/sec	9.874 ms	3113/ 3199	<97%>
[ID]	Interval	Transfer	Bandwidth	Jitter	Lost/Total	Datagrams
[1928]	1200.0-1201.0	sec 123 KB	tes 1.01 Mbits/sec	6.701 ms	3120/ 3206	<97%>
[1928]	1201.0-1202.0	sec 122 KB	tes 1000 Kbits/sec	8.762 ms	3124/ 3209	<97%>



Experimental Results (cont'd)

❖ Packet Loss

➤ every 11th packet drop

```
C:\WINDOWS\system32\cmd.exe - hrping.exe 168.188.48.204 -t -
Reply from 168.188.48.204: seq=0033 time=0.245ms TTL=128 ID=66ab
Reply from 168.188.48.204: seq=0034 time=0.242ms TTL=128 ID=66ac
Reply from 168.188.48.204: seq=0035 time=0.247ms TTL=128 ID=66ad
Request timed out.
Reply from 168.188.48.204: SEQ=0037 time=0.317ms TTL=128 ID=66ae
Reply from 168.188.48.204: seq=0038 time=0.236ms TTL=128 ID=66af
Reply from 168.188.48.204: seq=0039 time=0.180ms TTL=128 ID=66b0
Reply from 168.188.48.204: seq=003a time=0.304ms TTL=128 ID=66b1
Reply from 168.188.48.204: seq=003b time=0.296ms TTL=128 ID=66b2
Reply from 168.188.48.204: seq=003c time=0.182ms TTL=128 ID=66b3
Reply from 168.188.48.204: seq=003d time=0.229ms TTL=128 ID=66b4
Reply from 168.188.48.204: seq=003e time=0.240ms TTL=128 ID=66b5
Reply from 168.188.48.204: seq=003f time=0.275ms TTL=128 ID=66b6
Reply from 168.188.48.204: seq=0040 time=0.263ms TTL=128 ID=66b7
Request timed out.
Reply from 168.188.48.204: SEQ=0042 time=0.309ms TTL=128 ID=66b8
Reply from 168.188.48.204: seq=0043 time=0.229ms TTL=128 ID=66b9
Reply from 168.188.48.204: seq=0044 time=0.324ms TTL=128 ID=66ba
Reply from 168.188.48.204: seq=0045 time=0.227ms TTL=128 ID=66bb
Reply from 168.188.48.204: seq=0046 time=0.219ms TTL=128 ID=66bc
Reply from 168.188.48.204: seq=0047 time=0.257ms TTL=128 ID=66bd
Reply from 168.188.48.204: seq=0048 time=0.257ms TTL=128 ID=66be
Reply from 168.188.48.204: seq=0049 time=0.317ms TTL=128 ID=66bf
Reply from 168.188.48.204: seq=004a time=0.237ms TTL=128 ID=66c0
Reply from 168.188.48.204: seq=004b time=0.234ms TTL=128 ID=66c1
Request timed out.
Reply from 168.188.48.204: SEQ=004d time=0.288ms TTL=128 ID=66c2
Reply from 168.188.48.204: seq=004e time=0.307ms TTL=128 ID=66c3
Reply from 168.188.48.204: seq=004f time=0.232ms TTL=128 ID=66c4
Reply from 168.188.48.204: seq=0050 time=0.240ms TTL=128 ID=66c5
Reply from 168.188.48.204: seq=0051 time=0.240ms TTL=128 ID=66c6
```

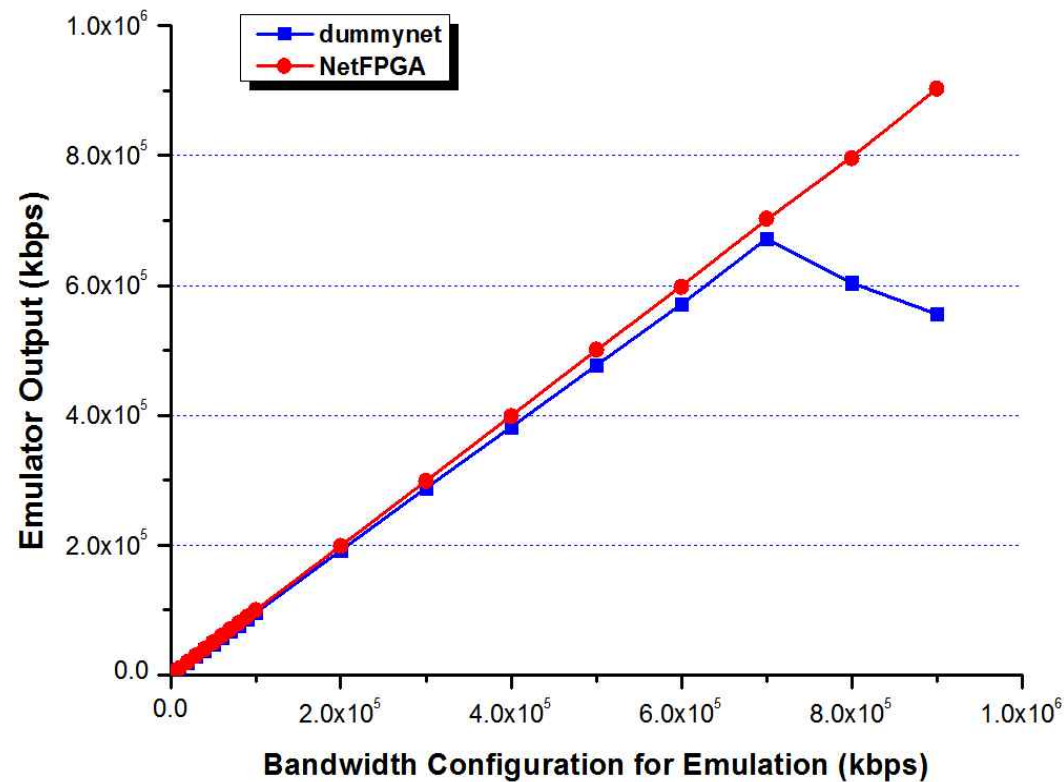
```
Reply from 168.188.48.204: seq=0052 time=0.240ms TTL=128 ID=66c7
Reply from 168.188.48.204: seq=0053 time=0.313ms TTL=128 ID=66c8
Reply from 168.188.48.204: seq=0054 time=0.296ms TTL=128 ID=66c9
Reply from 168.188.48.204: seq=0055 time=0.227ms TTL=128 ID=66ca
Reply from 168.188.48.204: seq=0056 time=0.278ms TTL=128 ID=66cb
Request timed out.
Reply from 168.188.48.204: SEQ=0058 time=0.319ms TTL=128 ID=66cc
Reply from 168.188.48.204: seq=0059 time=0.350ms TTL=128 ID=66cd
Reply from 168.188.48.204: seq=005a time=0.246ms TTL=128 ID=66ce
Reply from 168.188.48.204: seq=005b time=0.324ms TTL=128 ID=66cf
Reply from 168.188.48.204: seq=005c time=0.320ms TTL=128 ID=66d0
Reply from 168.188.48.204: seq=005d time=0.250ms TTL=128 ID=66d1
Reply from 168.188.48.204: seq=005e time=0.204ms TTL=128 ID=66d2
Reply from 168.188.48.204: seq=005f time=0.188ms TTL=128 ID=66d3
Reply from 168.188.48.204: seq=0060 time=0.287ms TTL=128 ID=66d4
Reply from 168.188.48.204: seq=0061 time=0.517ms TTL=128 ID=66d5
Request timed out.
Reply from 168.188.48.204: SEQ=0063 time=0.317ms TTL=128 ID=66d6
Reply from 168.188.48.204: seq=0064 time=0.335ms TTL=128 ID=66d7
Reply from 168.188.48.204: seq=0065 time=0.313ms TTL=128 ID=66d8
Reply from 168.188.48.204: seq=0066 time=0.228ms TTL=128 ID=66d9
Reply from 168.188.48.204: seq=0067 time=0.188ms TTL=128 ID=66da
Reply from 168.188.48.204: seq=0068 time=0.244ms TTL=128 ID=66db
Reply from 168.188.48.204: seq=0069 time=0.715ms TTL=128 ID=66dc
Reply from 168.188.48.204: seq=006a time=0.233ms TTL=128 ID=66dd
Reply from 168.188.48.204: seq=006b time=0.305ms TTL=128 ID=66de
Reply from 168.188.48.204: seq=006c time=0.311ms TTL=128 ID=66df
Request timed out.
Reply from 168.188.48.204: SEQ=006e time=0.321ms TTL=128 ID=66e0
Reply from 168.188.48.204: seq=006f time=0.771ms TTL=128 ID=66e1
Reply from 168.188.48.204: seq=0070 time=0.185ms TTL=128 ID=66e2
Reply from 168.188.48.204: seq=0071 time=0.243ms TTL=128 ID=66e3
Reply from 168.188.48.204: seq=0072 time=0.265ms TTL=128 ID=66e4
Reply from 168.188.48.204: seq=0073 time=0.307ms TTL=128 ID=66e5
Reply from 168.188.48.204: seq=0074 time=0.183ms TTL=128 ID=66e6
Reply from 168.188.48.204: seq=0075 time=0.319ms TTL=128 ID=66e7
Reply from 168.188.48.204: seq=0076 time=0.190ms TTL=128 ID=66e8
Reply from 168.188.48.204: seq=0077 time=0.224ms TTL=128 ID=66e9
```



NetFPGA vs. Dummynet

❖ Emulation of Bottleneck Bandwidth

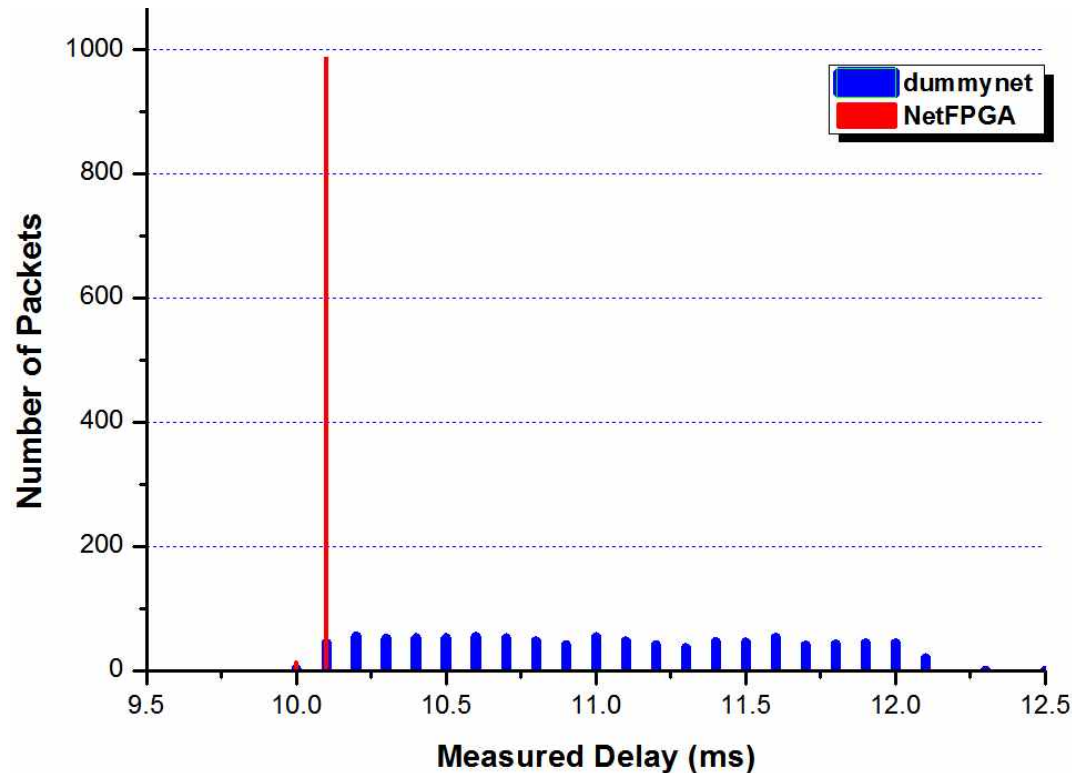
- The NetFPGA emulator can emit exact throughput almost up to 1 Gbps, but the output of the Dummynet is saturated around 700 or 800 Mbps.



NetFPGA vs. Dummynet (cont'd)

❖ Emulation of Packet Delay

- NetFPGA emulator is very accurate according to the configured value, but the Dummynet has more diverse variation. (10 ms, 1000 ping packets)



NetFPGA vs. Dummynet (cont'd)

❖ Emulation of Packet loss

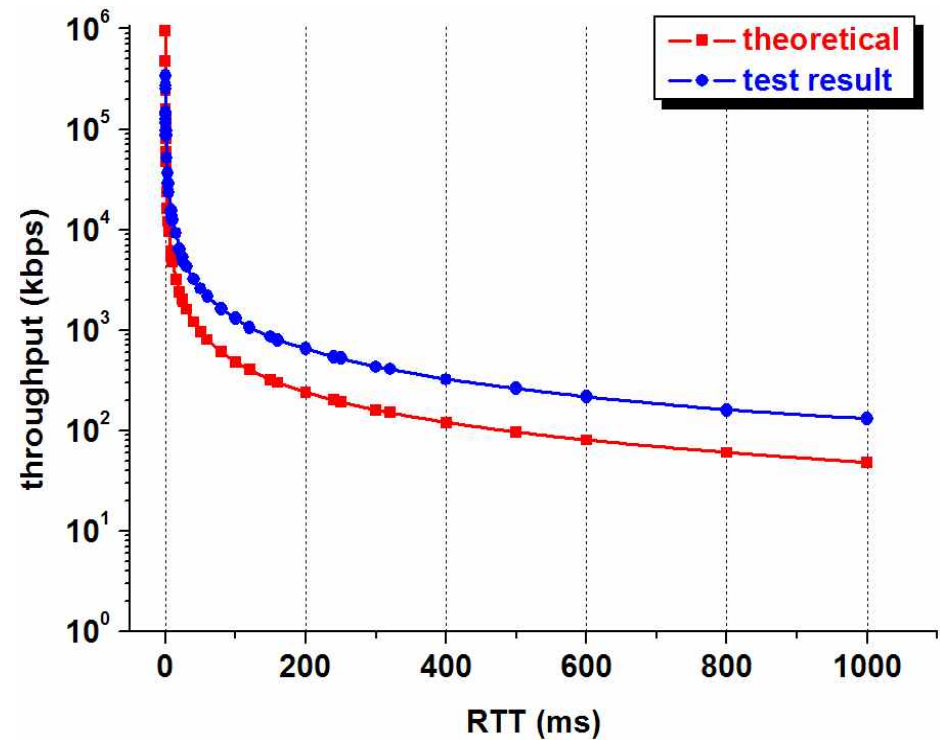
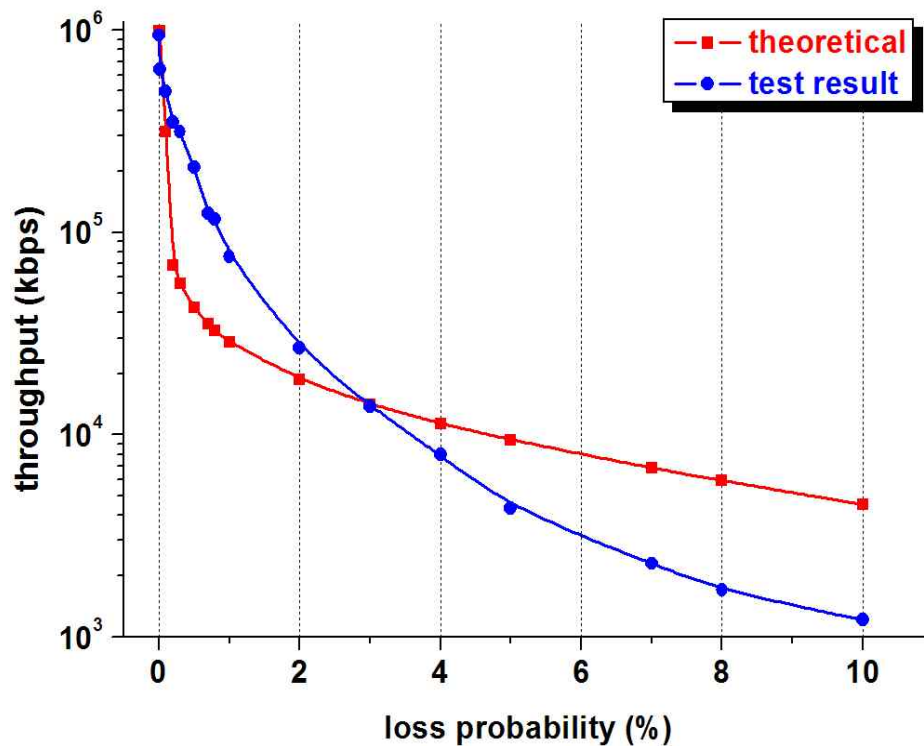
- NetFPGA emulator can control more exactly
- Exact mean value and very small variance of loss probability

Loss Probability Configuration		0.1%	1%	5%	10%
NetFPGA Result	mean	0.100062	1.00111	5.004734	10.11184
	variance	4.26e-11	2.39e-10	7.63e-10	2.22e-09
Dummynet Result	mean	0.099667	0.997294	4.939374	9.754387
	variance	9.72e-11	2.96e-10	2.21e-09	6.93e-09

Application to TCP throughput performance

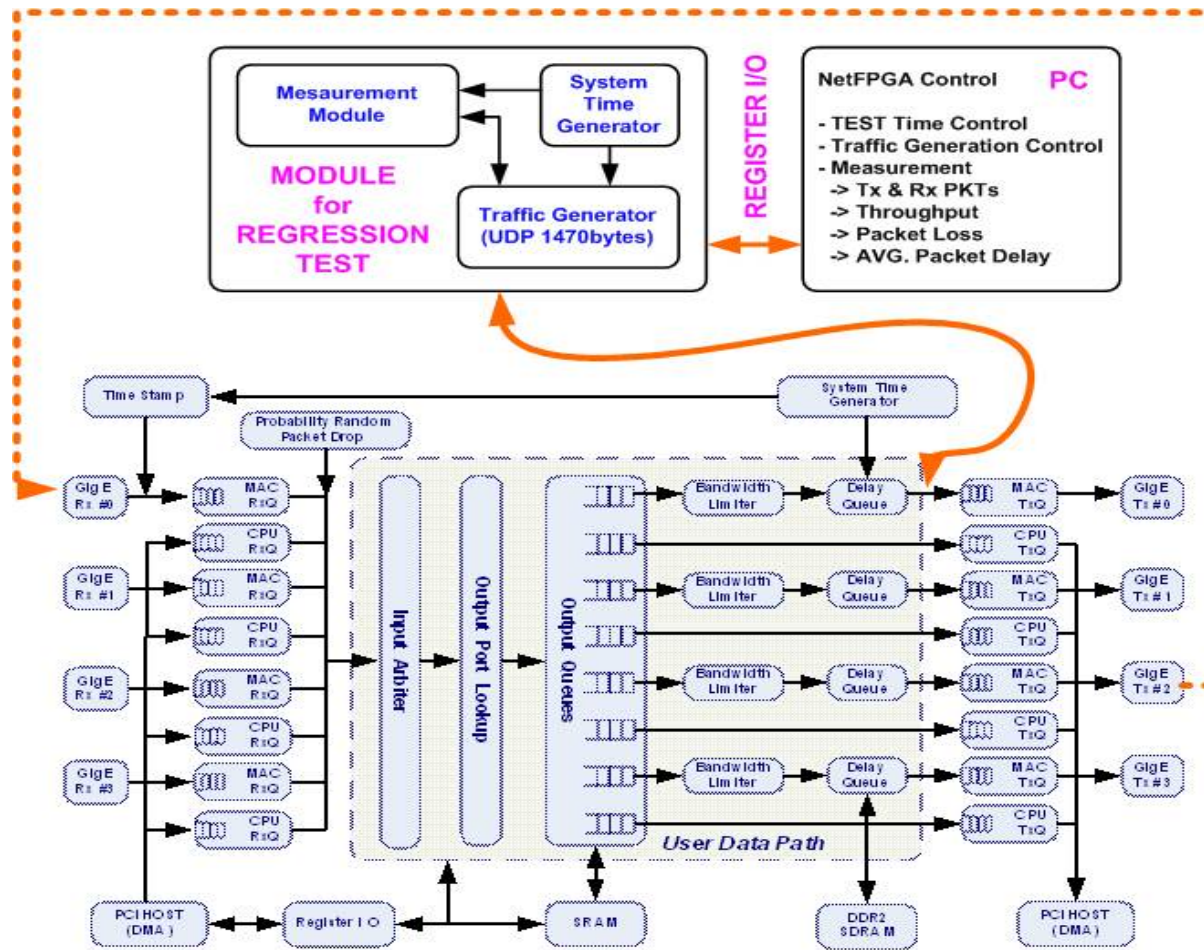
❖ Measurement of the Throughput Performance

$$\text{Throughput}(\text{TCP} / \text{Reno}) = \frac{1}{RTT} \sqrt{\frac{3}{2p}}$$



Demonstration

❖ Scheme of the Regression Test





Demonstration (cont'd)

❖ Regression Test

➤ Scenario #1

- ❑ Verifying the Regression Test Module

➤ Scenario #2

- ❑ Verifying the Bandwidth Limiter Module

➤ Scenario #3

- ❑ Verifying the Packet Delay Module

➤ Scenario #4

- ❑ Verifying the Packet Drop Module



Scenario #1

❖ Verifying the Regression Test Module

- Without packet loss, packet delay and bottleneck bandwidth.
- Regression test is working correctly?

```
Regression Test for Network Emulator (rev 0.90)

minsh@cnu.ac.kr

Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
*****

-> This test will Verify the regression test module ...

-> If you don't want, press Ctrl-C to exit ...

-> Test Set-up Start ...

Register Reset ..... OK !!!

-> Test Set-up Status ...

Packet Loss Probability ..... 0.000 %
Bottleneck Bandwidth ..... 1 Gbps
Packet Delay ..... 0.000 us

-> Test Start ...

Last packet scheduled for transmission within 180.000 sec

Sending packets..... Elapsed 180.000 sec

-> Tx & Rx statistics ...

PKT Gen Time : 180.000 sec
PKT Size : 1512 bytes (MAC, UDP: 1470 bytes)
Tx PKTs : 14648682
Rx PKTs : 14648682
Drop PKTs : 0

-> Final Reports ...

0] Test Time : 180.000 sec
1] Generated Traffic : 938.789 Mbps
2] Throughput : 938.789 Mbps
3] Loss Ratio : 0.000 %
4] Avg. Delay : 0.001 msec

-> Test Finish ...

Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
*****
```



Scenario #2

❖ Verifying the Bandwidth Limiter Module

- Only with bottleneck bandwidth (without packet loss and delay)

```
-> Test Start ...

Last packet scheduled for transmission within 180.000 sec

Sending packets..... Elapsed 180.000 sec

*****
Regression Test for Network Emulator (rev 0.90)
minsh@cnu.ac.kr

Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
*****

-> This test will Verify the bandwidth limiter module ...

-> If you don't want, press Ctrl-C to exit ...

-> Test Set-up Start ...

Register Reset ..... OK !!!

-> Test Set-up Status ...

Packet Loss Probability ..... 0.000 %
Bottleneck Bandwidth ..... 1.000 Mbps
Packet Delay ..... 0.000 us

-> Tx & Rx statistics ...

PKT Gen Time : 180.000 sec
PKT Size : 1512 bytes (MAC, UDP: 1470 bytes)
Tx PKTs : 14648682
Rx PKTs : 15475
Drop PKTs : 14633207

-> Final Reports ...

0] Test Time : 180.000 sec
1] Generated Traffic : 938.789 Mbps
2] Throughput : 0.992 Mbps
3] Loss Ratio : 99.894 %
4] Avg. Delay : 1.730 msec

-> Test Finish ...

Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
*****
```



Scenario #3

❖ Verifying the Packet Drop Module

- Only with packet drop (without packet delay and bottle bandwidth)

-> Test Start ...

Last packet scheduled for transmission within 180.000 sec

Sending packets..... Elapsed 180.000 sec

```
*****
Regression Test for Network Emulator (rev 0.90)

minsh@cnu.ac.kr

Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
*****
```

-> Tx & Rx statistics ...

```
PKT Gen Time : 180.000 sec
PKT Size     : 1512 bytes (MAC, UDP: 1470 bytes)
Tx PKTs      : 14648682
Rx PKTs      : 13915242
Drop PKTs    : 733440
```

-> If you don't want, press Ctrl-C to exit ...

-> Final Reports ...

-> Test Set-up Start ...

```
0] Test Time       : 180.000 sec
1] Generated Traffic : 938.789 Mbps
2] Throughput      : 891.785 Mbps
3] Loss Ratio      : 5.007 %
4] Avg. Delay      : 0.001 msec
```

Register Reset OK !!!

-> Test Set-up Status ...

```
Packet Loss Probability ..... 5.000 %
Bottleneck Bandwidth ..... 1 Gbps
Packet Delay ..... 0.000 us
```

-> Test Finish ...

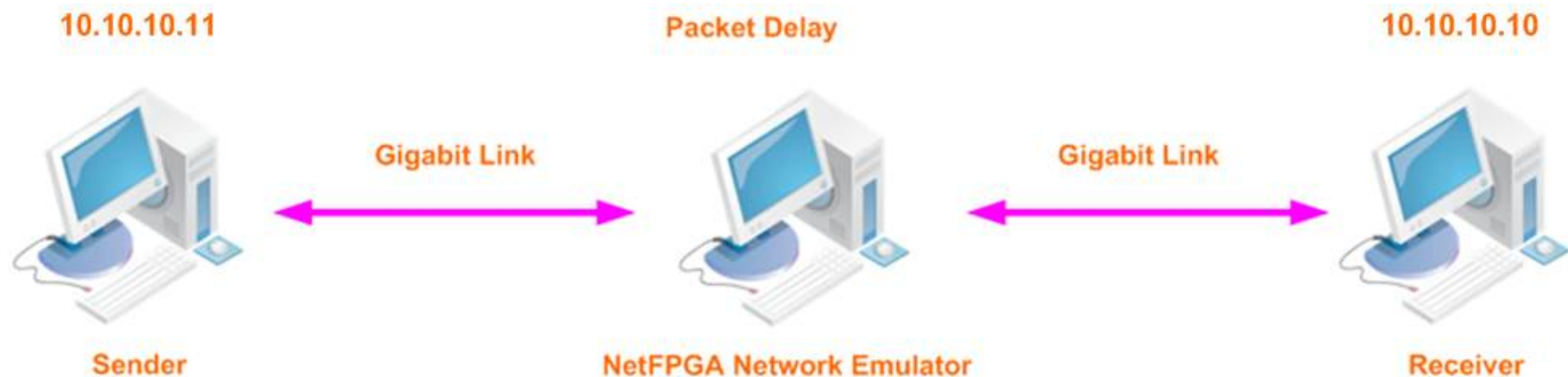
```
Data Communications & Next Generation Networks Lab.
Dept. of Infocomm. Eng., Chungnam National University, Korea.
```



Scenario #4

❖ Verifying the Packet Delay Module

- Only with packet delay (without packet loss and bottleneck bandwidth)
- Ping test between sender and receiver through the NetFPGA network emulator
- Ping 10.10.10.10 -i 0.001 (1ms)





References

- ❖ Dummynet, <http://www.dummynet.com>.
- ❖ NISTNet, <http://www-x.antd.nist.gov/nistnet>.
- ❖ NetFPGA, http://netfpga.org/foswiki/bin/view/NetFPGA/OneGig/Guide#Walkthrough_the_Reference_Designs.
- ❖ G.Adam Covington, Glen Gibb, John Lockwood, and Nick McKeown, “A Packet Generator on the NetFPGA Platform” , IEEE Symposium on. Field-Programmable Custom Computing Machines (FCCM), April 2009.
- ❖ iperf, <http://sorceforge.net/projects/lperf>.
- ❖ Matthew Mathis, Jeffery Semke, Jamshid Mahdavi, Teunis Ott, “The Macroscopic Behavior of the TCP Congestion Avoidance Algorithm” , ACM SIGCOMM, vol 27, no 3, July 1997.

***Thank you
for your attention !!!***

