
ExpertTCP™ - TCP Throughput Testing (per RFC-6349)



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- **Background**
 - RFC-2544, Y.1564 (SAM), RFC-6349, SLA
- **TCP Principles**
 - TCP Throughput Inter-Relationships
 - Bandwidth * Delay Product
 - Bottleneck Bandwidth (BB)
 - TCP Congestion Window (TCP CWND) and TCP Receive Window (RWND)
 - Packet Loss Rate
 - Retransmission Schemes (Go Back N, Selective Repeat)
- **GL Hardware Platforms**

Performance Testing of Packet / Ethernet Connections and Networks

For Predictable
Managed Networks

- RFC-2544
- ITU Y.1564 (SAM)
- RFC-6349 (TCP)

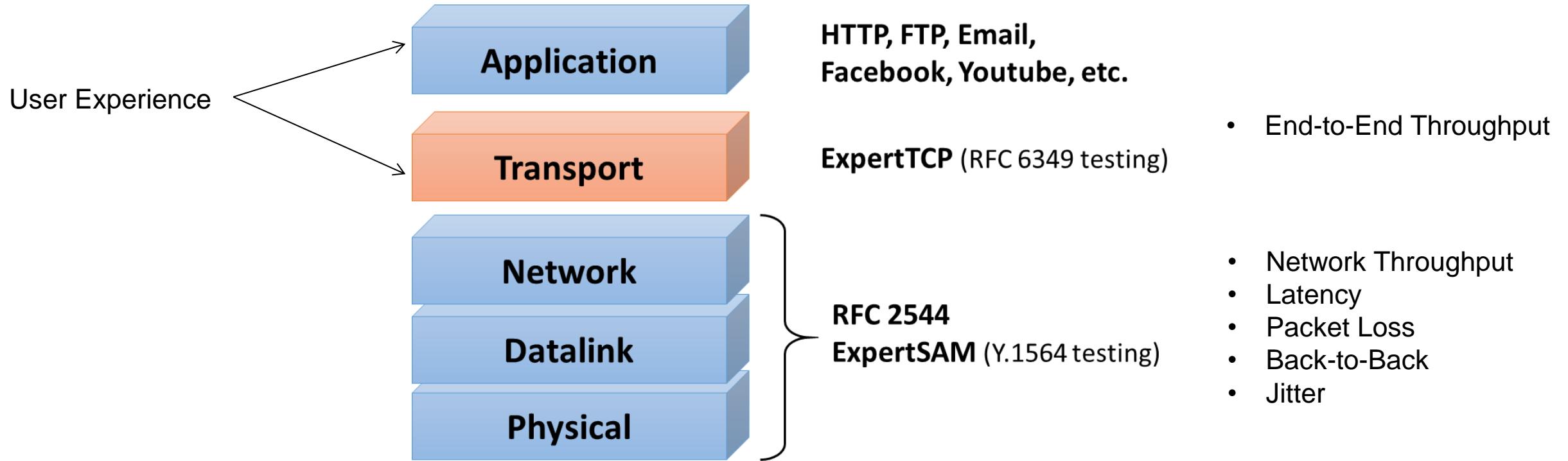
Service Level Agreements
from Network Providers, a must

User Experience,
Application-Network Sensitive,
TCP Tuning

SAM – Service Activation Methodology

TCP – Transmission Control Protocol

Packet / Ethernet Testing



Typical SLA

Typically

Packet Loss

0.0005 % to 1%

Latency

36 to 75 ms

Availability

99% to 99.9%

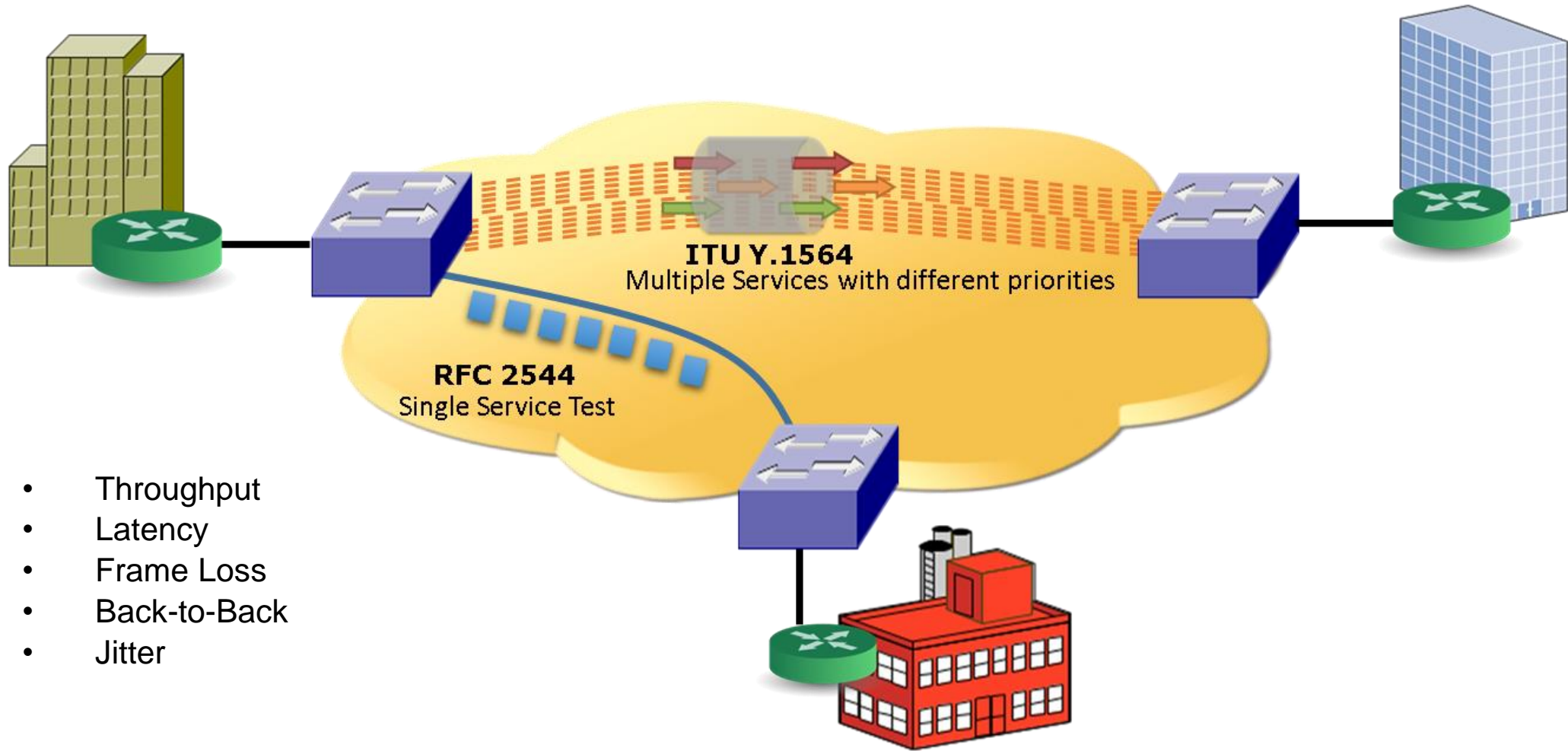
EXHIBIT D – Service Level Agreements

1. Service Level Agreement Matrix

| Category/Service | Service Level Agreement Metrics | | | | |
|---|---|--------------|--|--------|---------|
| | Mean Time To Repair | Availability | Packet Delivery or Loss | Jitter | Latency |
| Internet Services | | | | | |
| Internet Dedicated (North American IP Network Only) | 4 hrs to 8 hrs depending on access | 99.90% | ≥ 99.50% | ≤ 1 ms | ≤ 45 ms |
| SOHO Services | | | | | |
| Internet Cable | 24 hrs (Excludes Weekends and Holidays) | 99.00% | 99.00% | ≤ 4 ms | ≤ 75 ms |
| Internet DSL – Office & Solo | | | | | |
| Internet Satellite Enterprise & Office | N/A | 99.90% | ≤ 1 % | N/A | N/A |
| Managed PBX and VoIP Services | | | | | |
| Hosted IP Centrex | ≤ 4 hrs | 99.90% | EF- ≥ 99.995%, AF4x - ≥ 99.99% depending on access | ≤ 1 ms | ≤ 36 ms |
| IP Flexible T1, IP Integrated Access, IP Trunking | | | | | |

RFC-2544 vs. ITU Y.1564 (ExpertSAM™)

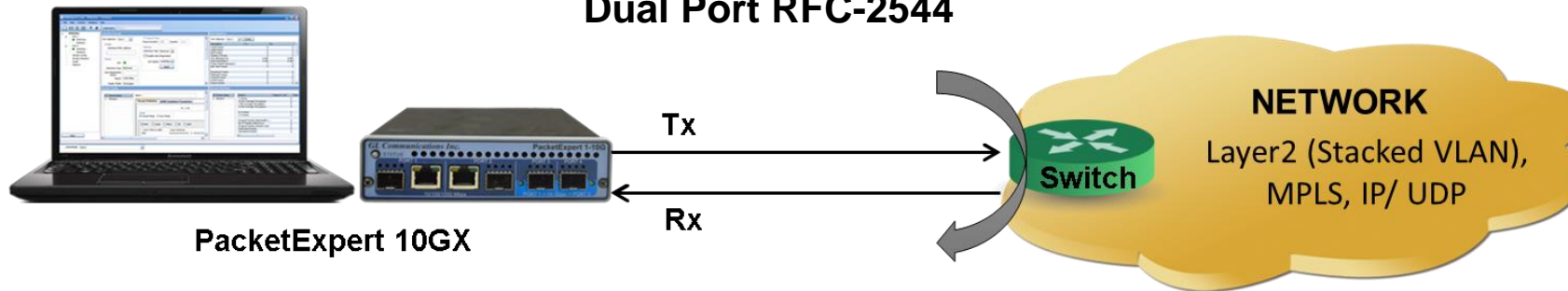
Both are Connectionless



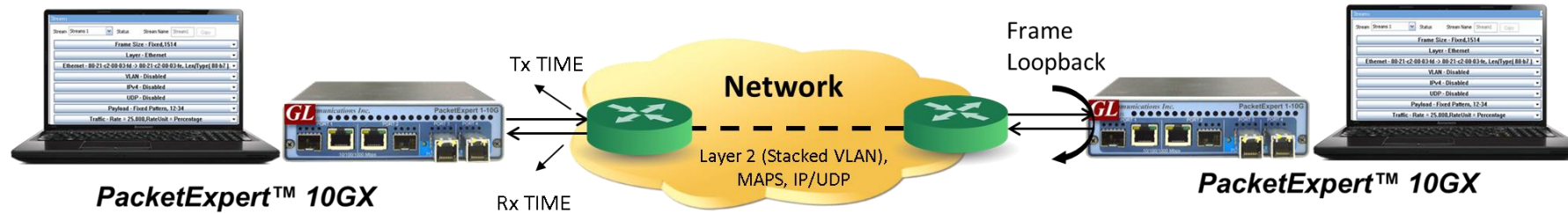
- Throughput
- Latency
- Frame Loss
- Back-to-Back
- Jitter

RFC-2544 Testing

Dual Port RFC-2544



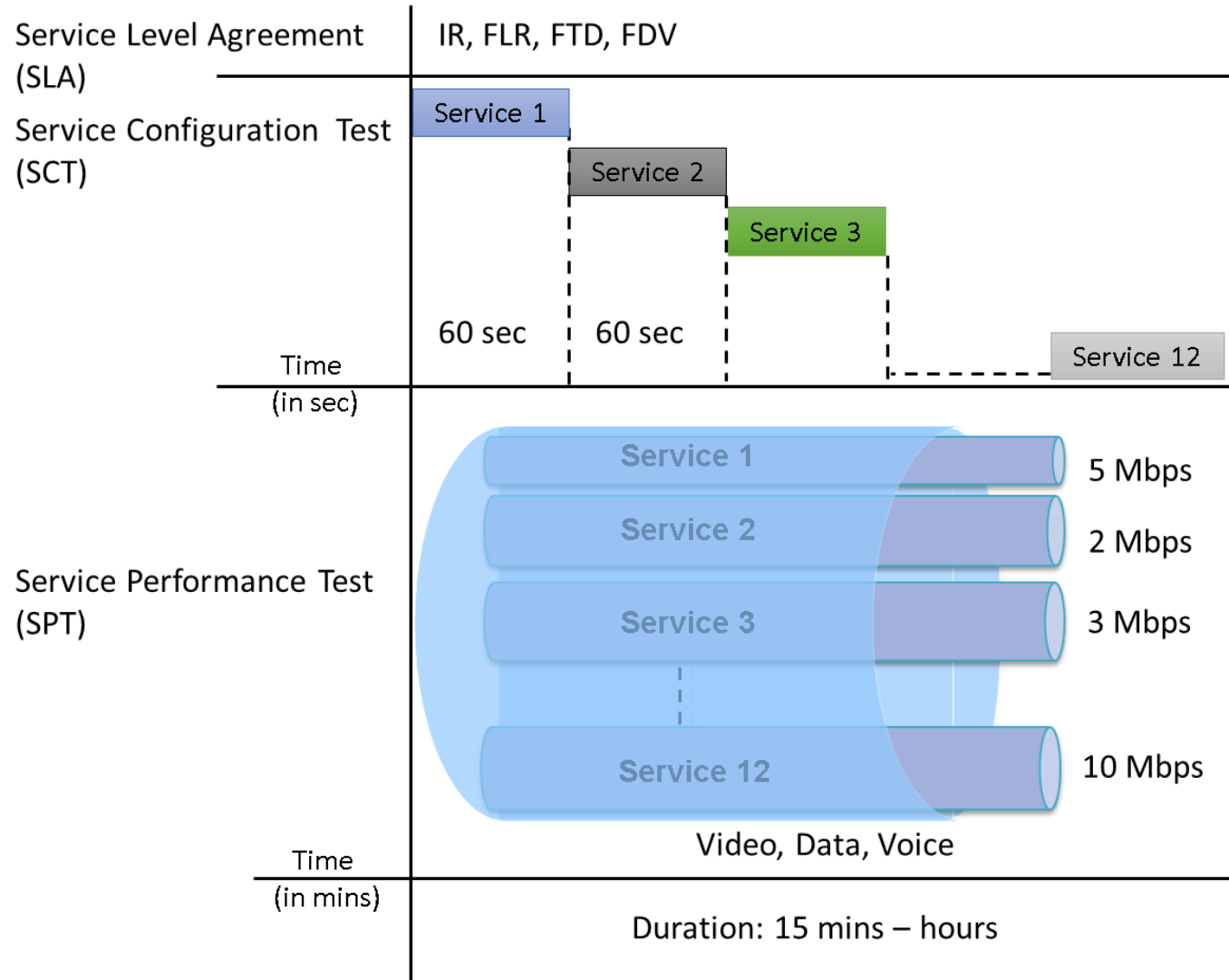
Single Port RFC-2544



$$\text{Latency} = \text{Rx TIME} - \text{Tx TIME}$$

- ExpertTCP™ testing is performed using the **RFC 6349** standard
- To conduct this test, users need two PacketExpert™ devices — one as the client and the other as the server
- The ExpertTCP™ test covers both upload (Client to Server) and download (Server to Client), measuring TCP throughput and efficiency
- RFC-2544 test application includes the following tests:
 - Throughput - Maximum number of frames per second that can be transmitted without any error
 - Latency - Measures the time required for a frame to travel from the originating device through the network to the destination device
 - Frame Loss - Measures the network's response in overload conditions
 - Back-to-Back - It measures the maximum number of frames received at full line rate before a frame is lost

ITU Y.1564 (ExpertSAM™)



Multi-Stream

- Throughput
- Latency
- Packet Loss
- Jitter

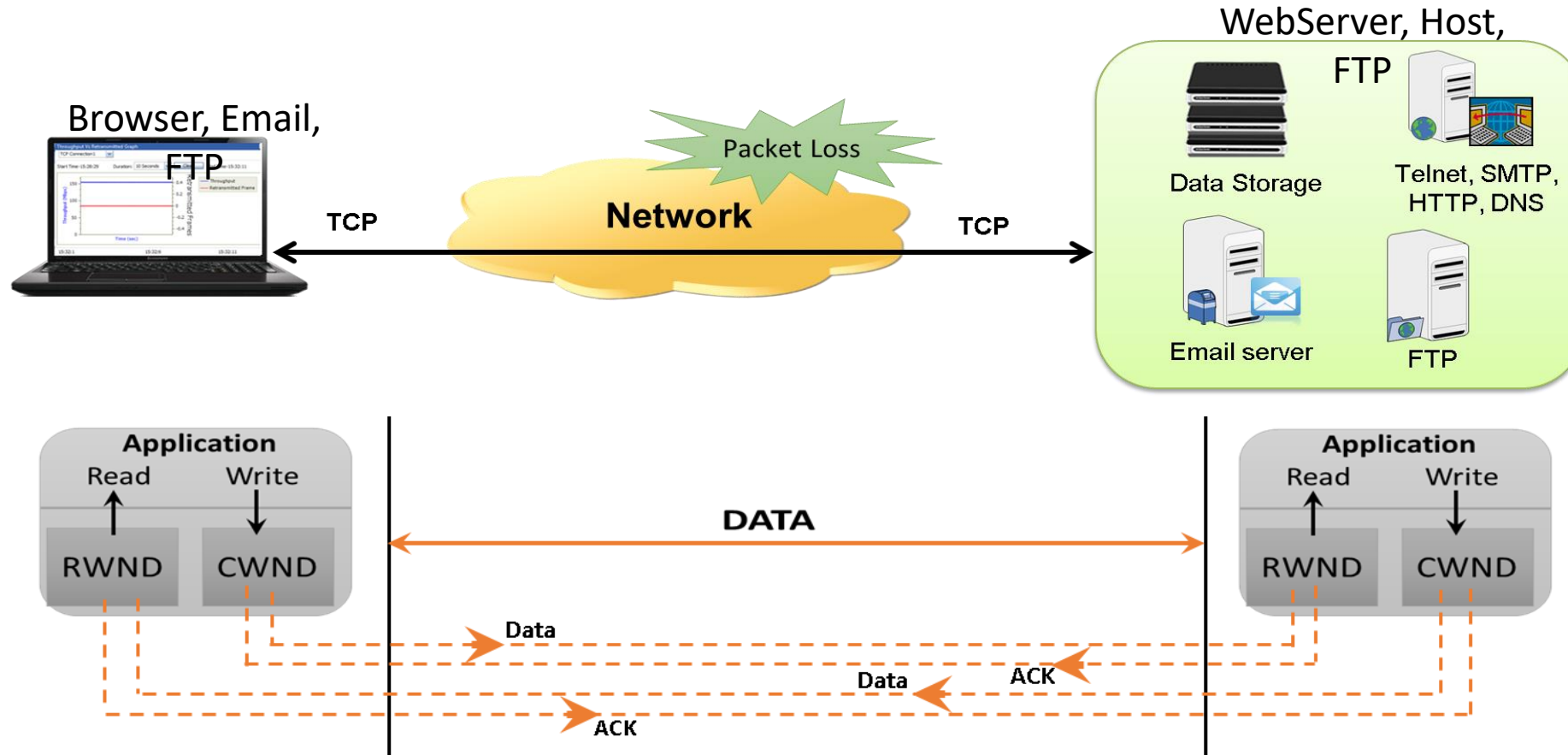
Testing Relevance

| Problems | RFC-2544 | Y.1564 | RFC-6349 |
|---|----------|--------|----------|
| Single-service Layer 2/ 3/ 4 SLA Issues like loss, jitter | Yes | Yes | N/A |
| Multi-service Layer 2/ 3/ 4 SLA Issues like loss, jitter | No | Yes | N/A |
| TCP window sizes (CPE issues) | No | No | Yes |
| Excessive retransmissions due to policing | No | No | Yes |

- Running RFC-2544, Y.1564 or another L2/L3 layer test is always first step
- However, even after these performance tests are passed with good results, end-customers can still complain that the “network is slow” and the cause of poor application performance (i.e., FTP, web browsing, etc.)
- Lack of TCP testing is a turn-up gap because end-customer applications are transported using TCP
- Save operating expense costs by eliminating or quickly resolving painful end-customer finger pointing scenarios

TCP Principle

(Packet Loss and Waiting for ACK Reduces Throughput)

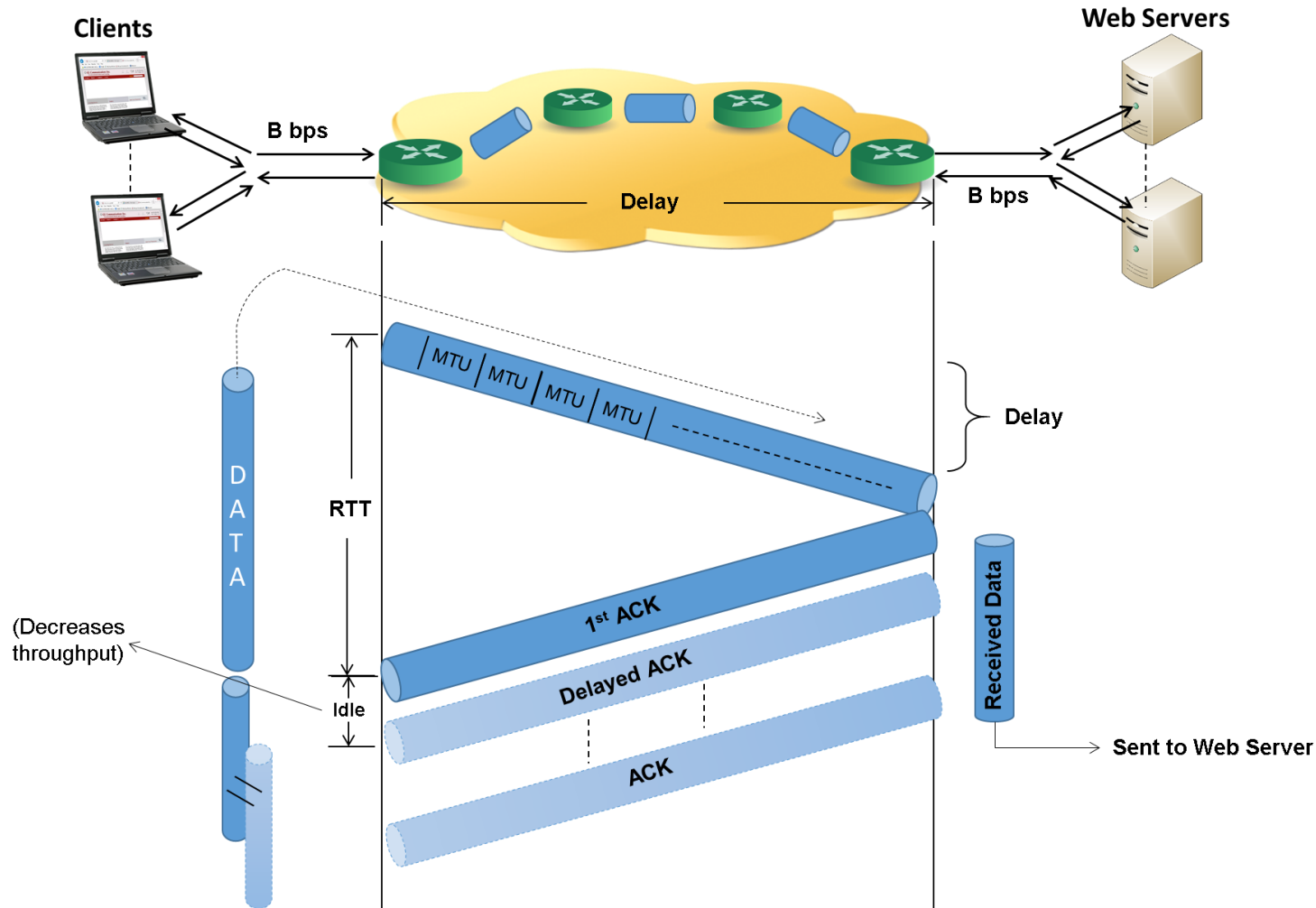


Major TCP Throughput Inter-Relationships

- Bandwidth of Applications
- Latency/Delay of Networks
- Packet Loss Networks
- TCP Retransmission Scheme
- Maximum Transmit Unit of Network
- Transmit/Receive Windows of TCP
- # of TCP Simultaneous Connections

Bandwidth Delay Product (Bits or Bytes)

Application and Network are Matched, TCP is Tuned



$B = 10 \text{ Mbps}$
 $RTT = 50 \text{ ms}$

$B * 50 = 500,000 \text{ bits}$
or $62,500 \text{ Bytes}$

$65,535 \text{ Bytes}$ is max
window

Achieving max
throughput

(Decreases
throughput)

Bandwidth (B) -

Bandwidth (bps), Mbps, the maximum rate at which an application can transmit or receive data (the smaller of the two). Line rate may be shared among applications

Bandwidth Delay Product (BDP) -

measured in bits or bytes (divided by 8), the number of bits (or bytes) in the network that are unacknowledged (in transit), $B \text{ (bps)} * RTT \text{ (secs)} = BDP \text{ bits}$

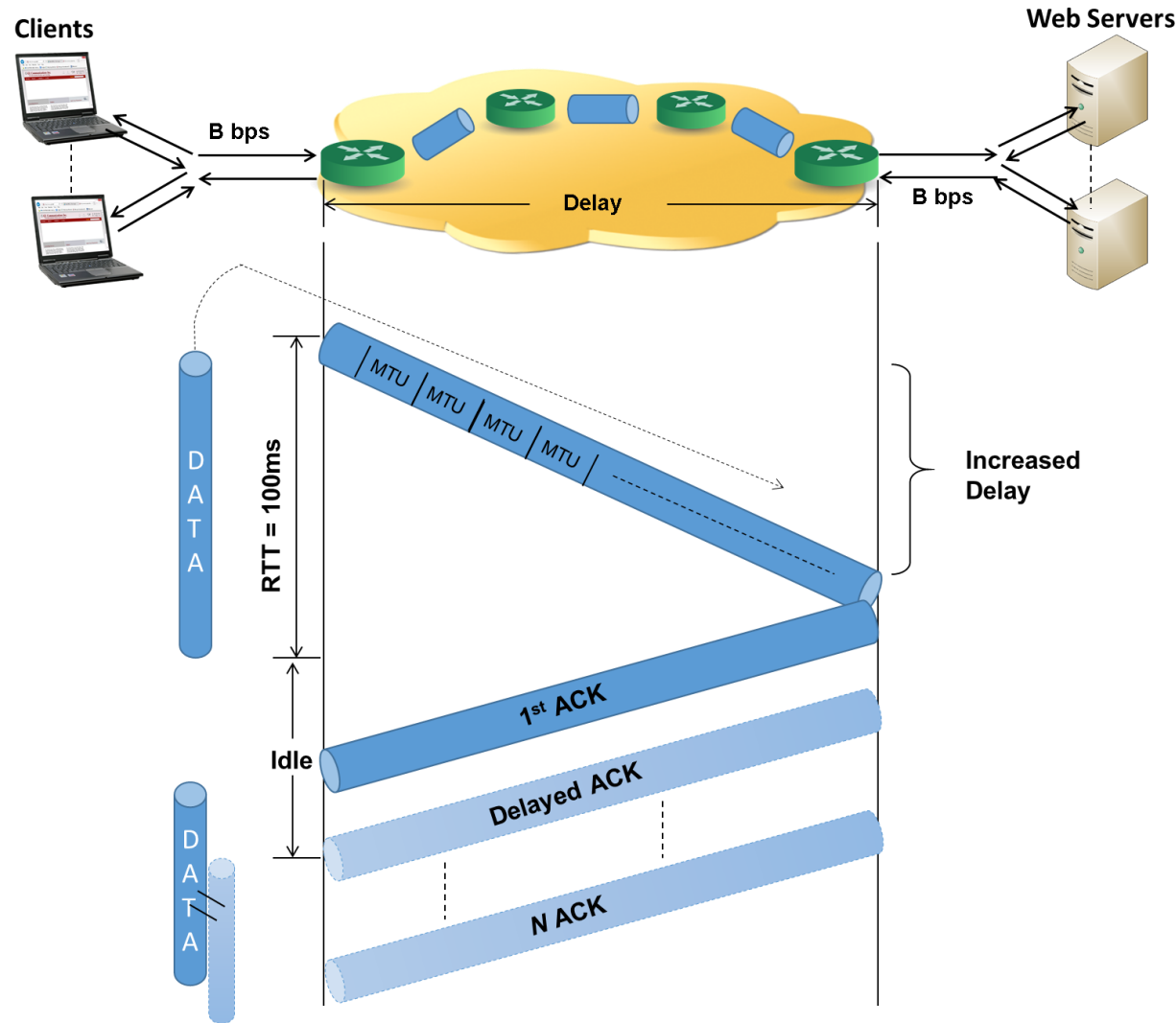
Effect of Increased Network Delay or Smaller Tx or Rx Buffers

$B = 10 \text{ Mbps}$
 $\text{RTT} = 100 \text{ ms}$

$B * 100 = 1,000,000 \text{ bits}$
or $125,000 \text{ Bytes}$

But $65,535 \text{ Bytes}$ is max window

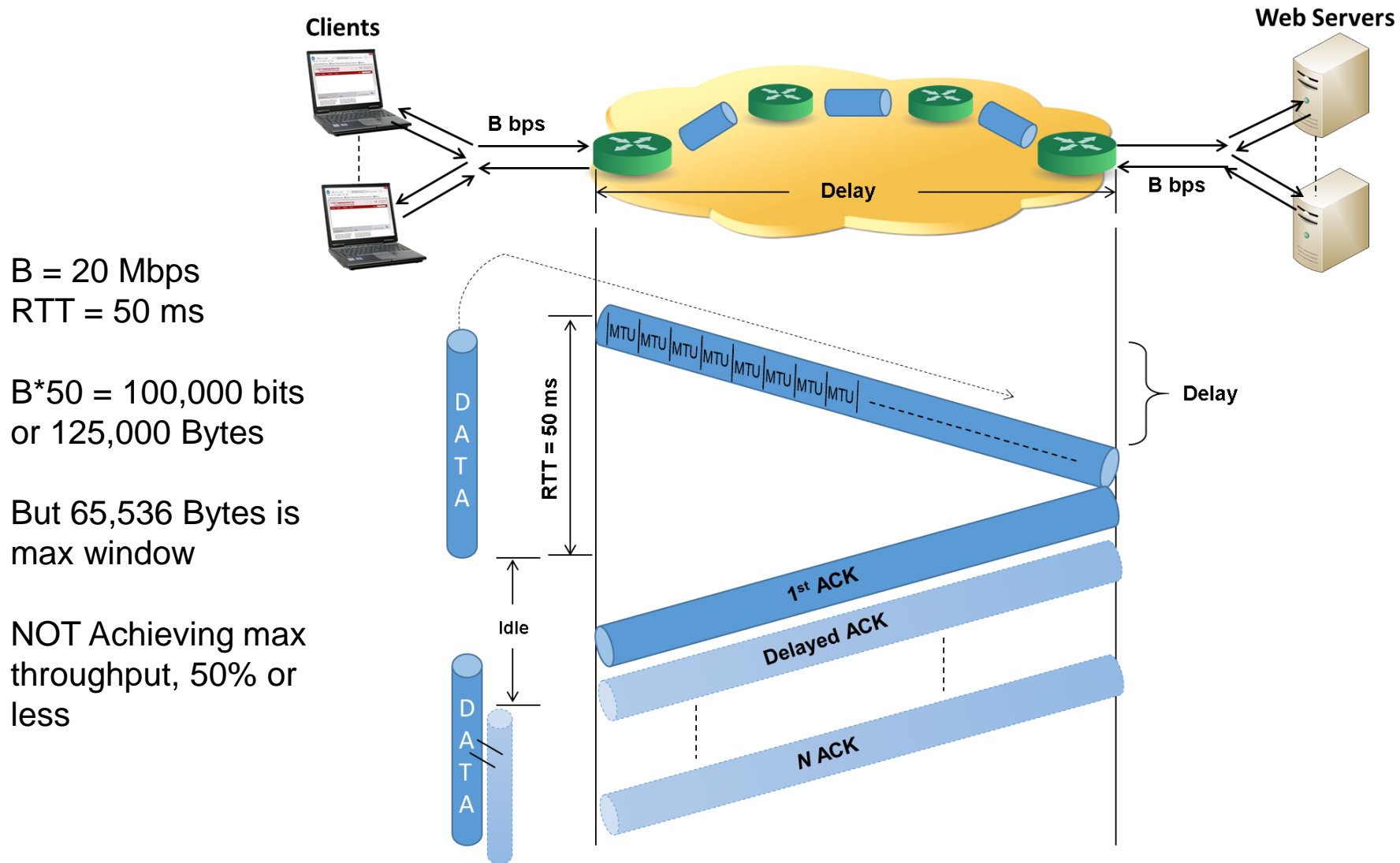
NOT Achieving max throughput, 50% or less



Latency, Delay, Round Trip Time (RTT) - in seconds (secs), or milliseconds (ms), round trip time includes acknowledgement delay

TCP Throughput - bits/second (bps), million bits/second (Mbps), One way throughput (RFC2544, Y.1564), Round-trip throughput (RFC-6349) is a different story since retransmissions and acknowledgements are involved.

Effect of Increased Application Bandwidth



$B = 20 \text{ Mbps}$
 $\text{RTT} = 50 \text{ ms}$

$B * 50 = 100,000 \text{ bits}$
or $125,000 \text{ Bytes}$

But $65,536 \text{ Bytes}$ is
max window

NOT Achieving max
throughput, 50% or
less

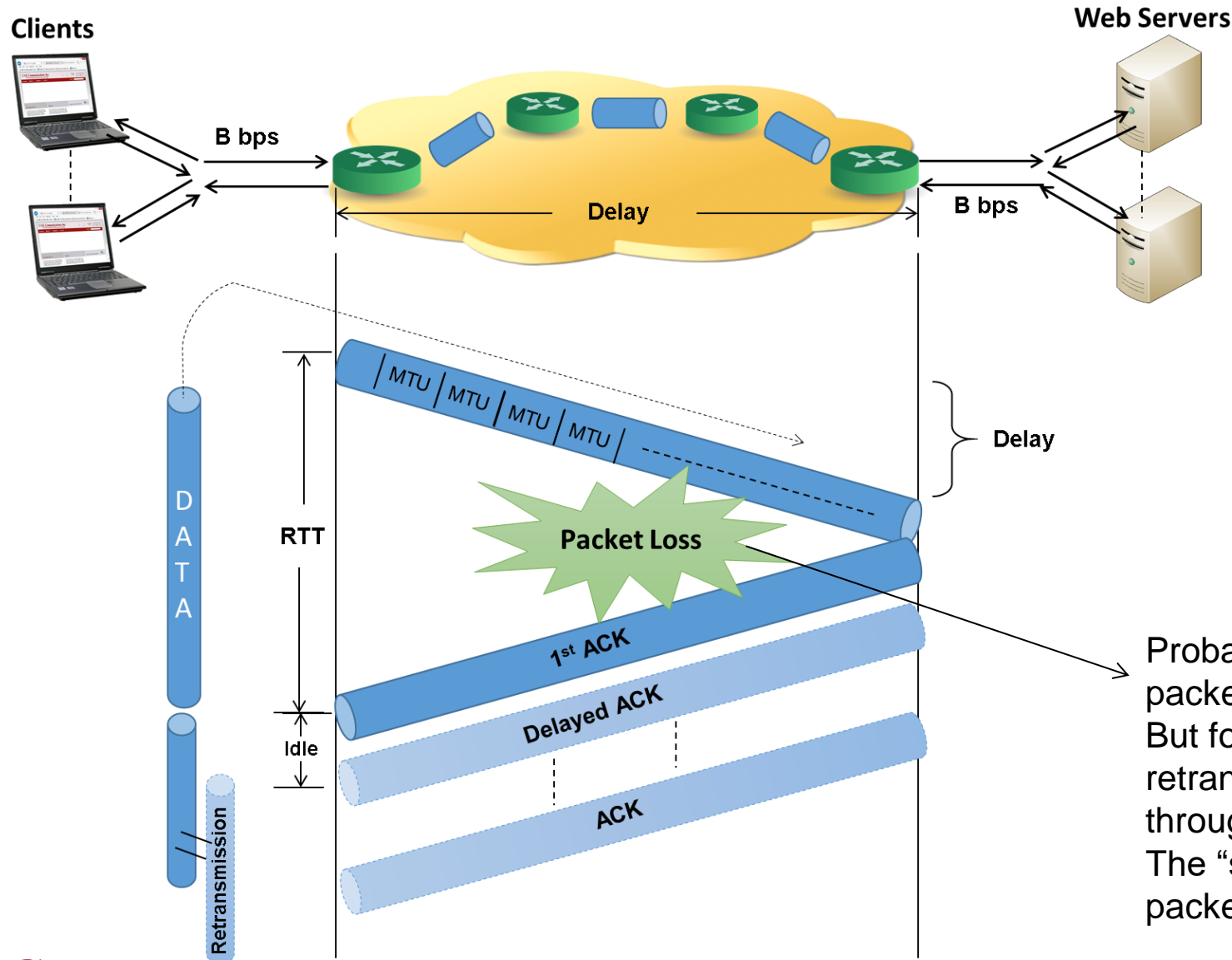
Maximum Transmission Unit (MTU) - Approx. 1500 bytes, max packet size

Jitter - Instantaneous variation in RTT, e.g. if RTT is nominally 100 ms, but varies from 80 ms to 120 ms, then jitter is $\pm 20 \text{ ms}$, or 40 ms. Since jitter affects ACK time, TCP throughput is affected

Packet Loss Rate - Very important factor affecting TCP throughput, could be as high as 2%

Excess Bandwidth may be used for additional TCP Connections

Effect of Packet Loss Rate and Retransmission Scheme



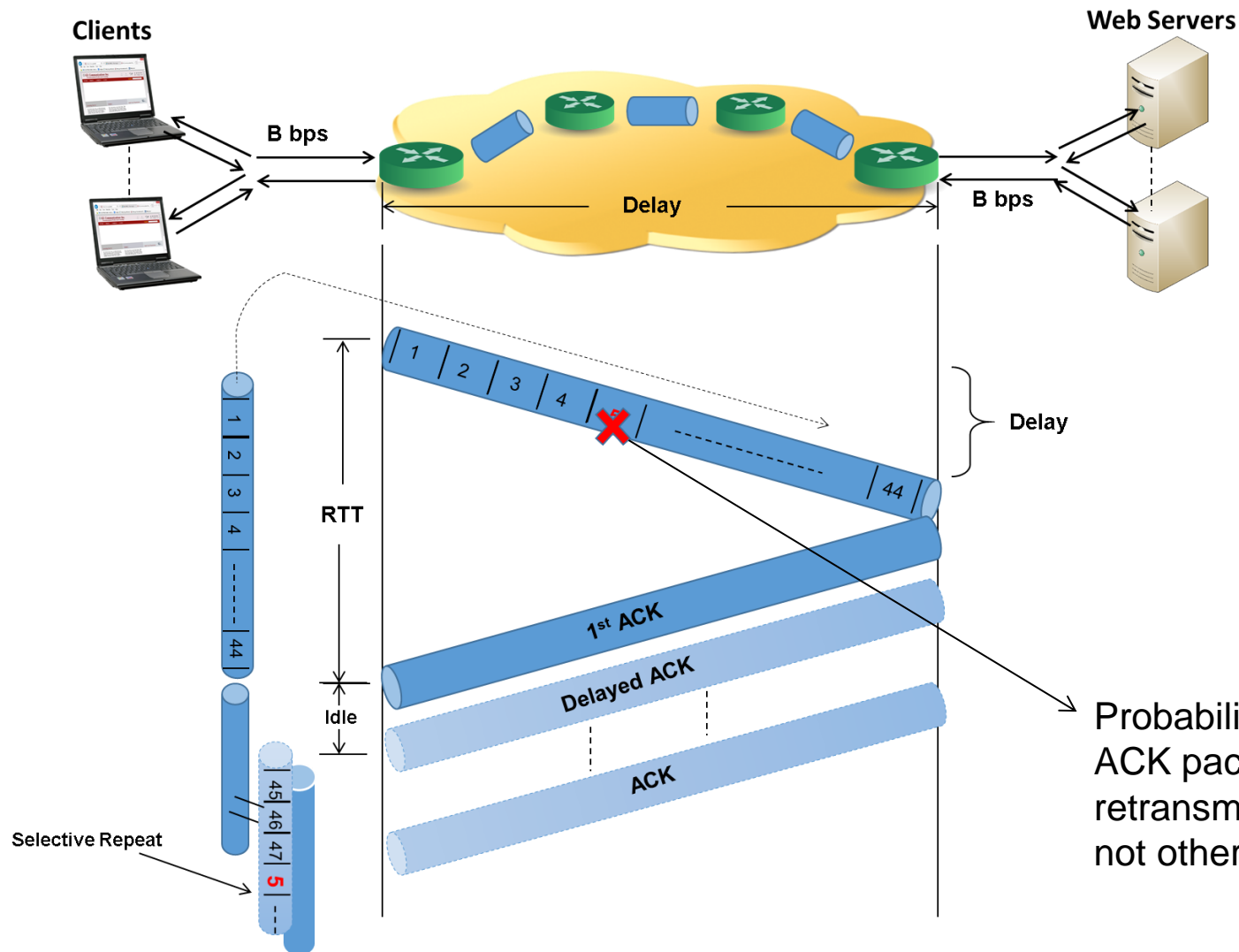
For **Go Back N** retransmission scheme, and if unacked packets is maximum ~ 43 or 44, then Packet Loss effects are very serious!

| Packet Loss | TCP Throughput |
|-------------|----------------|
|-------------|----------------|

| | |
|-------|-------|
| 0 % | 100% |
| 0.1 % | < 50% |
| 1 % | < 10% |
| 2 % | 0 % |

Probability that one or more MTU packets or ACK packets is lost is very high!! Can be 1 !!!
But for every lost MTU packet or ACK packet, 43 retransmissions occur. This results in near zero throughput.
The “slow start phase” results in very few “in flight” packets.

Effect of Packet Loss Rate and Retransmission Scheme (Contd.)



For **Selective Repeat** retransmission scheme, and if unacked packets is maximum ~ 43 or 44, then Packet Loss affects TCP Throughput linearly for “low” Packet Loss rates

| Packet Loss | TCP Throughput |
|-------------|----------------|
| 0 % | 100% |
| 0.1 % | > 99 % |
| 1 % | > 95 % |
| 2 % | ? % |

Probability that one or more MTU packets or ACK packets lost is very high! But the retransmission only affects the lost packets, not other packets.

ExpertTCP™ (RFC-6349 Testing)

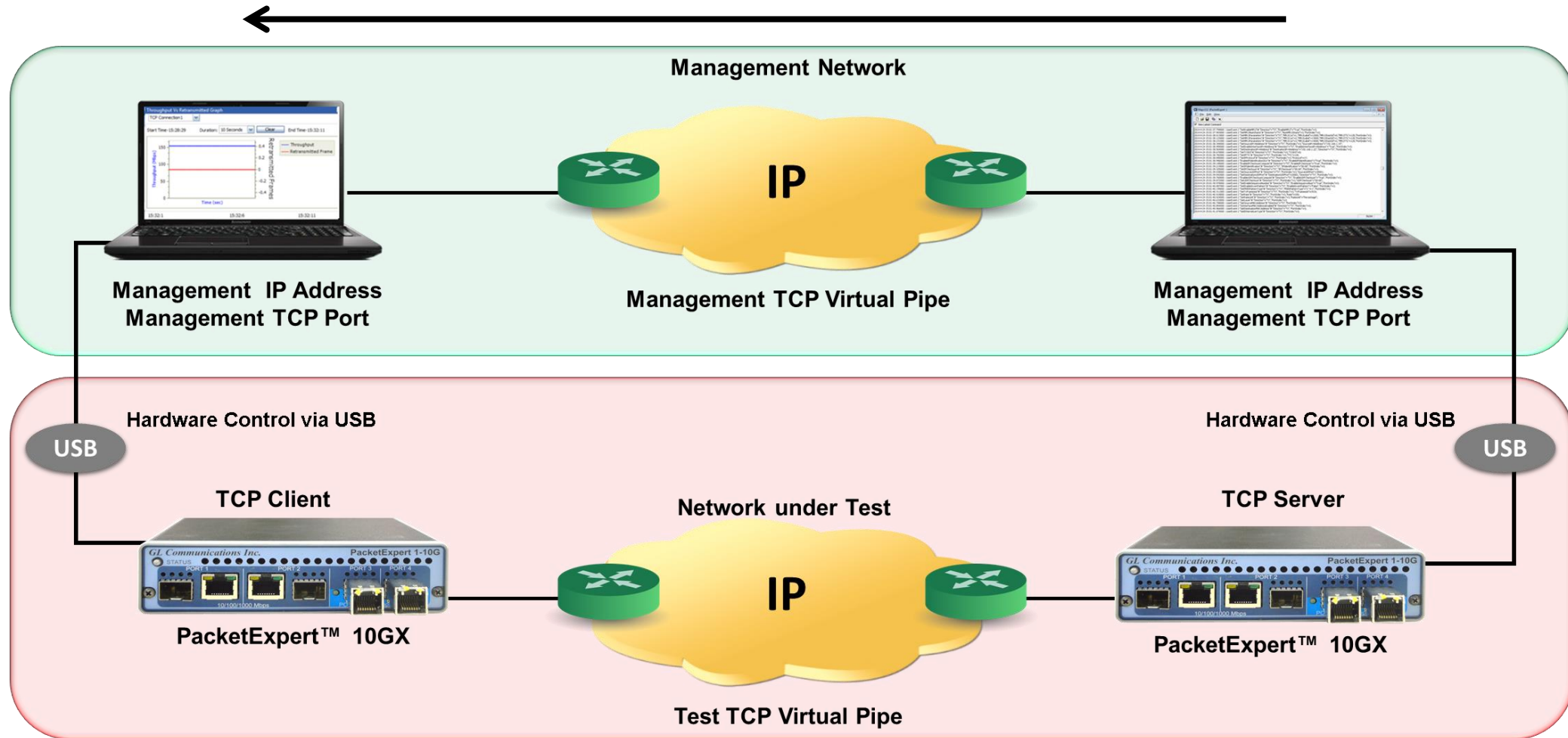
The TCP Throughput Testing is conducted in 3 steps simultaneously on up to 16 application streams:

- Path MTU Discovery - What is the maximum packet size that can successfully traverse the network?
- Round Trip Time (RTT) Measurement - Timestamp based RTT discovery of transmitted packet until acknowledgement packet arrives from far end.
- Measure TCP Throughput - Complete measurements per RFC-6349 definitions to provide TCP Throughput results.

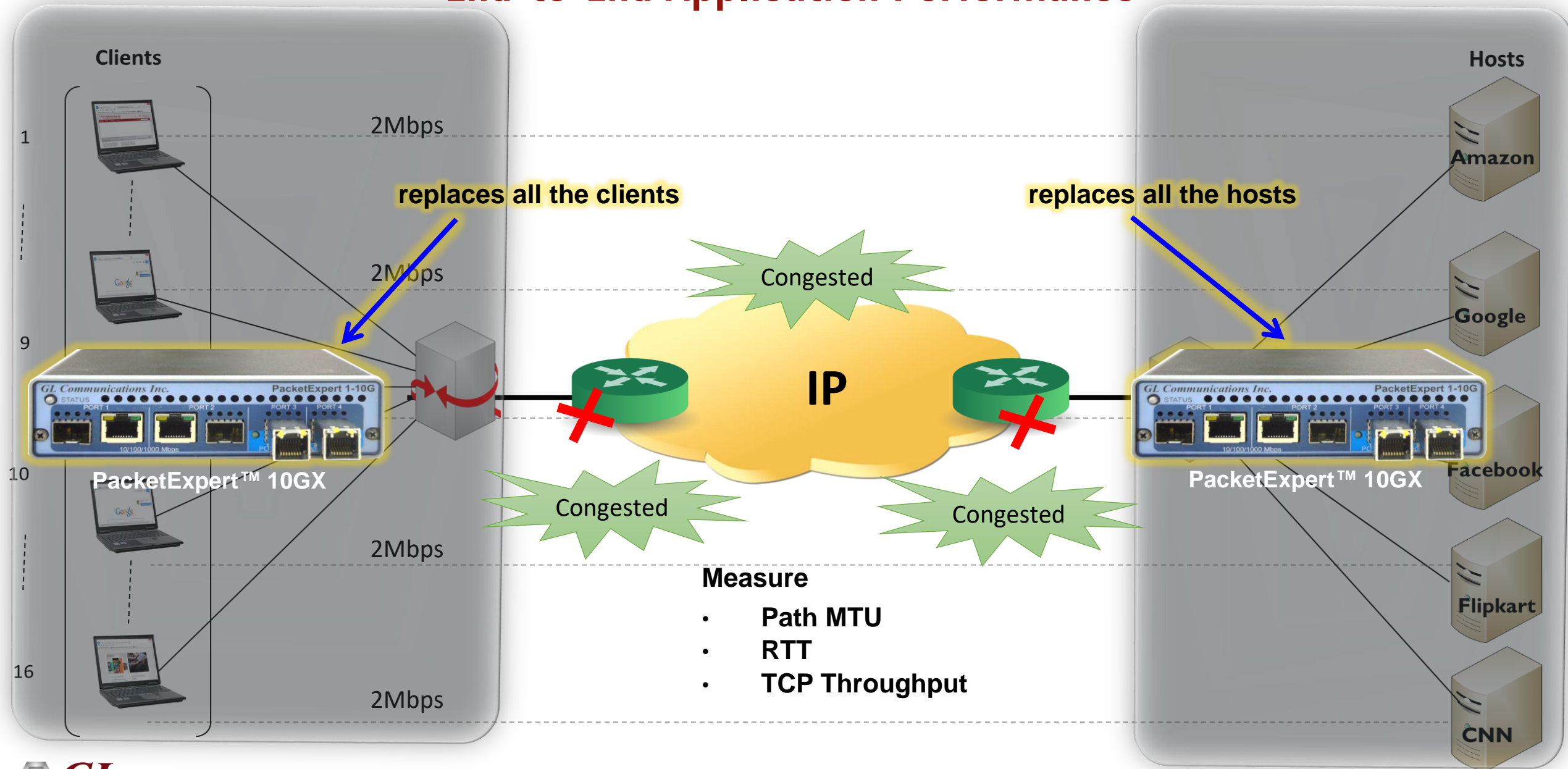
GL Hardware/Software ExpertTCP™

Basic Setup

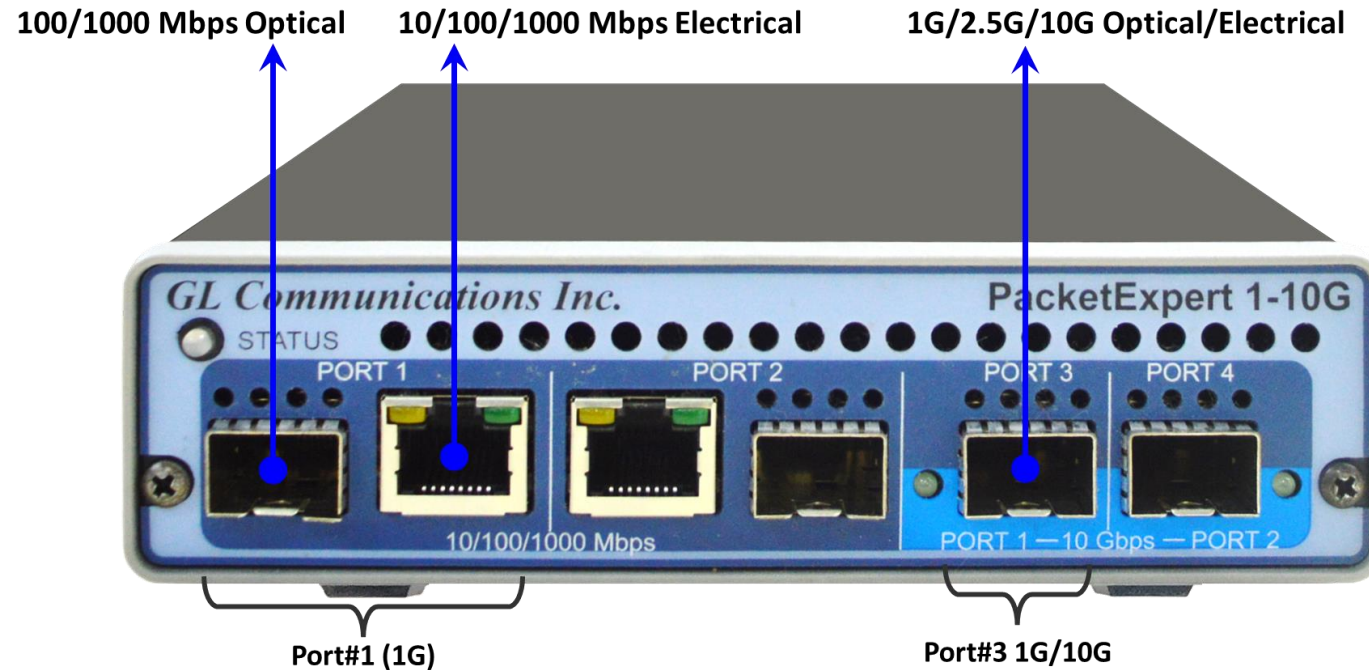
Test Configuration of Client and Server
Measurement Results from Server to Client



End-to-End Application Performance

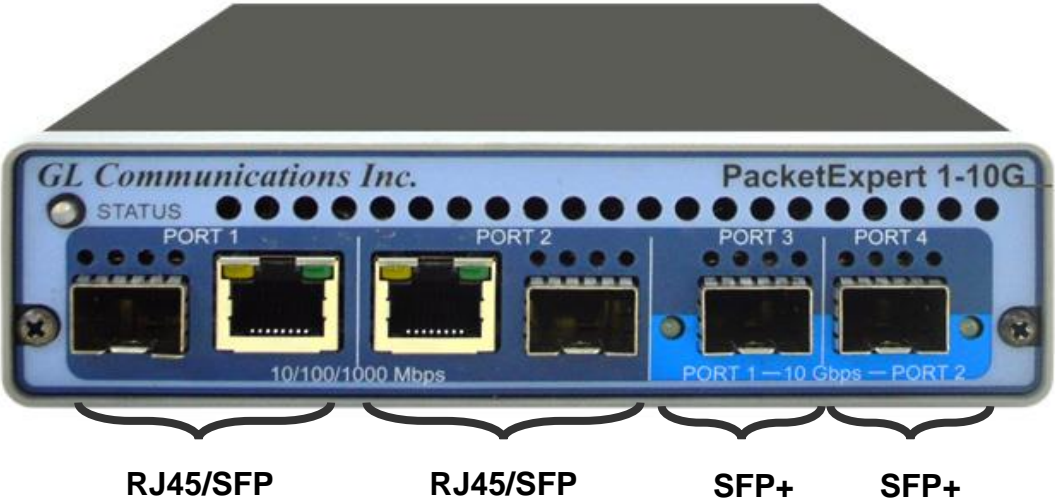


ExpertTCP™ 1G/2.5G/10G Ports



- **TCP Client and Server** will be supported in different applications
 - For 1G, **Port 1** is used
 - For 10G, **Port 3** is used

PacketExpert™ 10GX - Portable Unit (PXN100, PXN101)

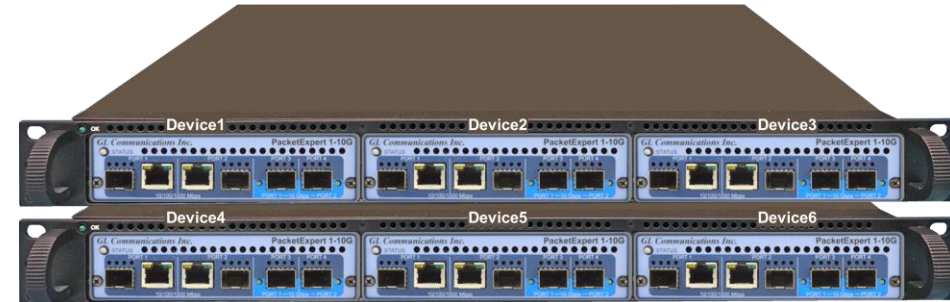


| | |
|-------------------------|--|
| Physical Specifications | <ul style="list-style-type: none">• Length: 8.45 in (214.63 mm)• Width: 5.55 in (140.97 mm)• Height: 1.60 in (40.64 mm)• Weight: 1.713 lbs |
| External Power Supply | <ul style="list-style-type: none">• +12 Volts (Medical Grade), 3 Amps (For portable units having serial number \geq 188400)• +9 Volts, 2 Amps (For portable units having serial number \geq 188400) |
| BUS Interface | <ul style="list-style-type: none">• USB 3.0• Optional 4-Port SMA Jack Trigger Board(TTL Input/Output) |
| Protocols | <ul style="list-style-type: none">• IEEE 802.3ae LAN PHY compliance• RFC 2544 compliance |

MTOP™ Rack Units



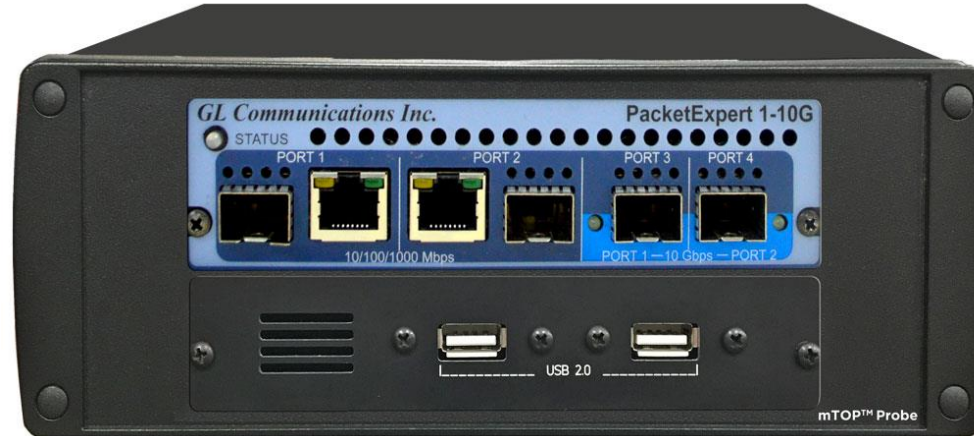
High Density 1U Rack option



Stacked High Density 1U Rack option

| | |
|-------------------------|---|
| Physical Specifications | <ul style="list-style-type: none">• Length: 16 in (406.4)• Width: 19 in (482.6)• Height: 1U / 2U |
| External Power Supply | <ul style="list-style-type: none">• ATX Power Supply |
| BUS Interface | <ul style="list-style-type: none">• 1U mTOP™ (MT001 + 3x PXN100)<ul style="list-style-type: none">➤ Rackmount Enclosure can support up to 3 PXN100s• 2U Rack Mount (with 6x PXN100)<ul style="list-style-type: none">➤ Rackmount Enclosure can support up to 6 PXN100s• Optional 4 to 12 Port SMA Jack Trigger Board (TTL Input/Output) |
| SBC Specifications | <ul style="list-style-type: none">• Intel Core i3 or optional i7 NUC Equivalent,• Windows® 11 64-bit Pro Operating System• USB 3.0 and USB 2.0 Ports• USB Type C Ports, Ethernet 2.5GigE port• 256 GB Hard drive, 8G Memory (Min)• Two HDMI ports |

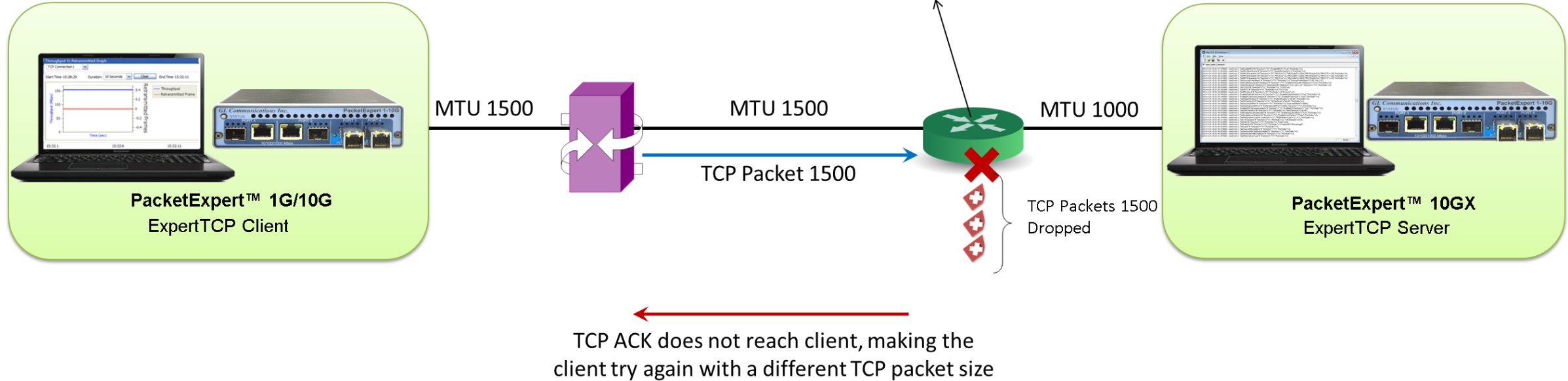
mTOP™ Probe with 10GX Hardware Unit + SBC



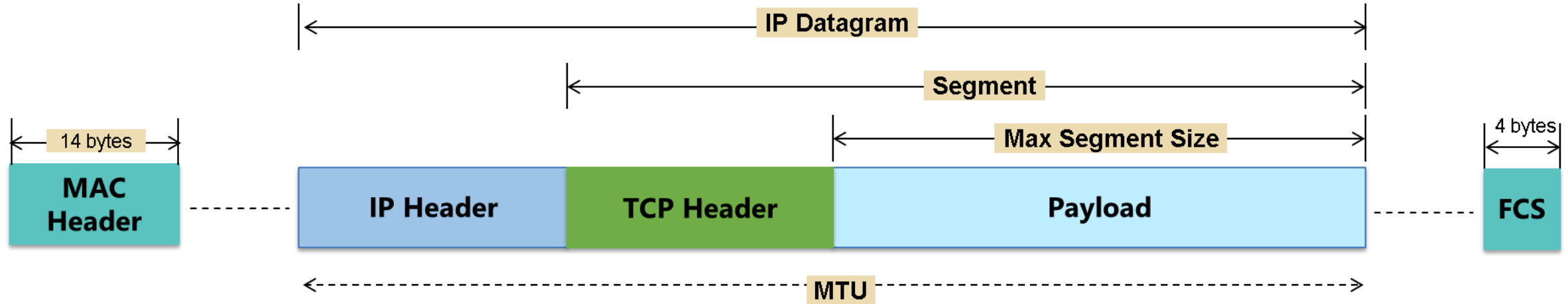
| | |
|-------------------------|--|
| Physical Specifications | <ul style="list-style-type: none">• Length: 10.4 in. (264.16 mm)• Width: 8.4 in. (213.36 mm)• Height: 3.0 in. (76.2 mm)• Optional 4-Port SMA Jack Trigger Board (TTL Input/Output)• External USB based Wi-Fi adaptor |
| External Power Supply | <ul style="list-style-type: none">• +12 Volts (Medical Grade), 3 Amps |
| SBC Specifications | <ul style="list-style-type: none">• Intel Core i3 or optional i7 NUC Equivalent,• Windows® 11 64-bit Pro Operating System• USB 3.0 and USB 2.0 Ports• USB Type C Ports, Ethernet 2.5GigE port• 256 GB Hard drive, 8G Memory (Min)• Two HDMI ports |

Step 1. Path MTU Discovery

Client sends packet with Don't Fragment (DF) bit set

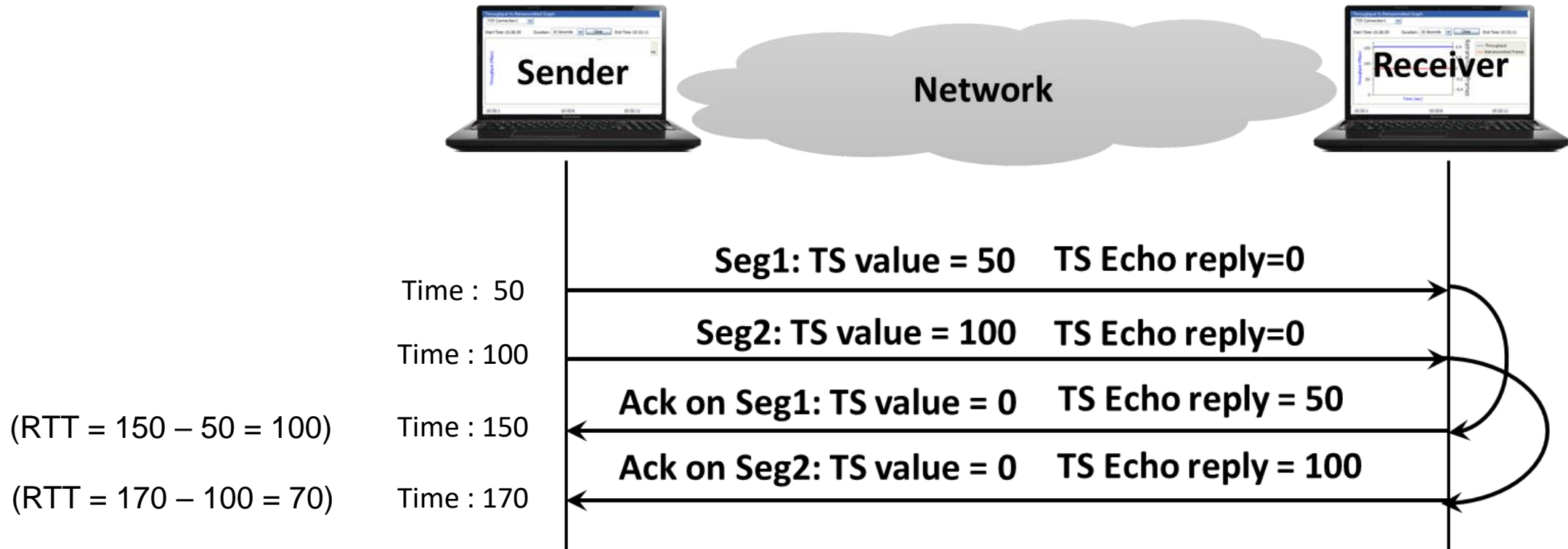


Step 1. Path MTU Discovery (Contd.)



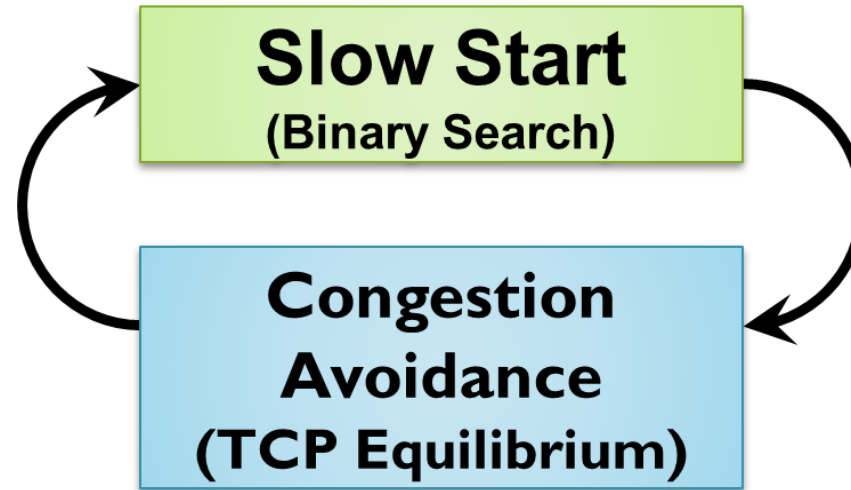
- Path MTU discovery as per RFC 4821 - PLPMTUD - Packetization Layer Path MTU Discovery
- DF (Do Not Fragment) bit is set to avoid fragmentation when traversing through network
- The algorithm uses TCP retransmit conditions to search for the MTU
- Each conclusive probe narrows the MTU search range, either by raising the lower limit on a successful probe or lowering the upper limit on a failed probe
- Path MTU is discovered for both directions in case of bi-directional test

Step 2. Timestamp based RTT Measurement

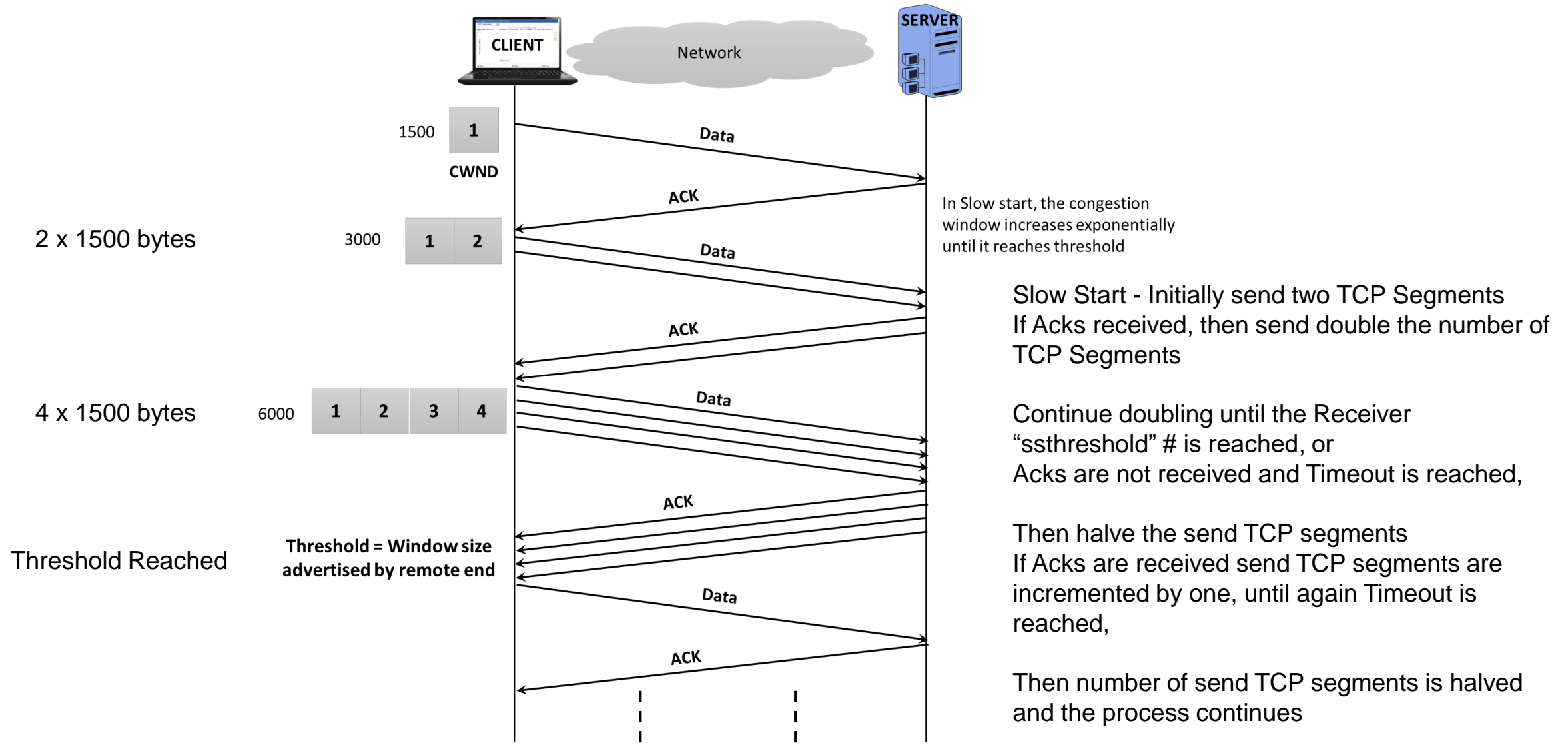


- Timestamp based RTT Measurement (RFC1323)
- Tx segment includes current time in option field, Receiver echoes timestamp in ACK

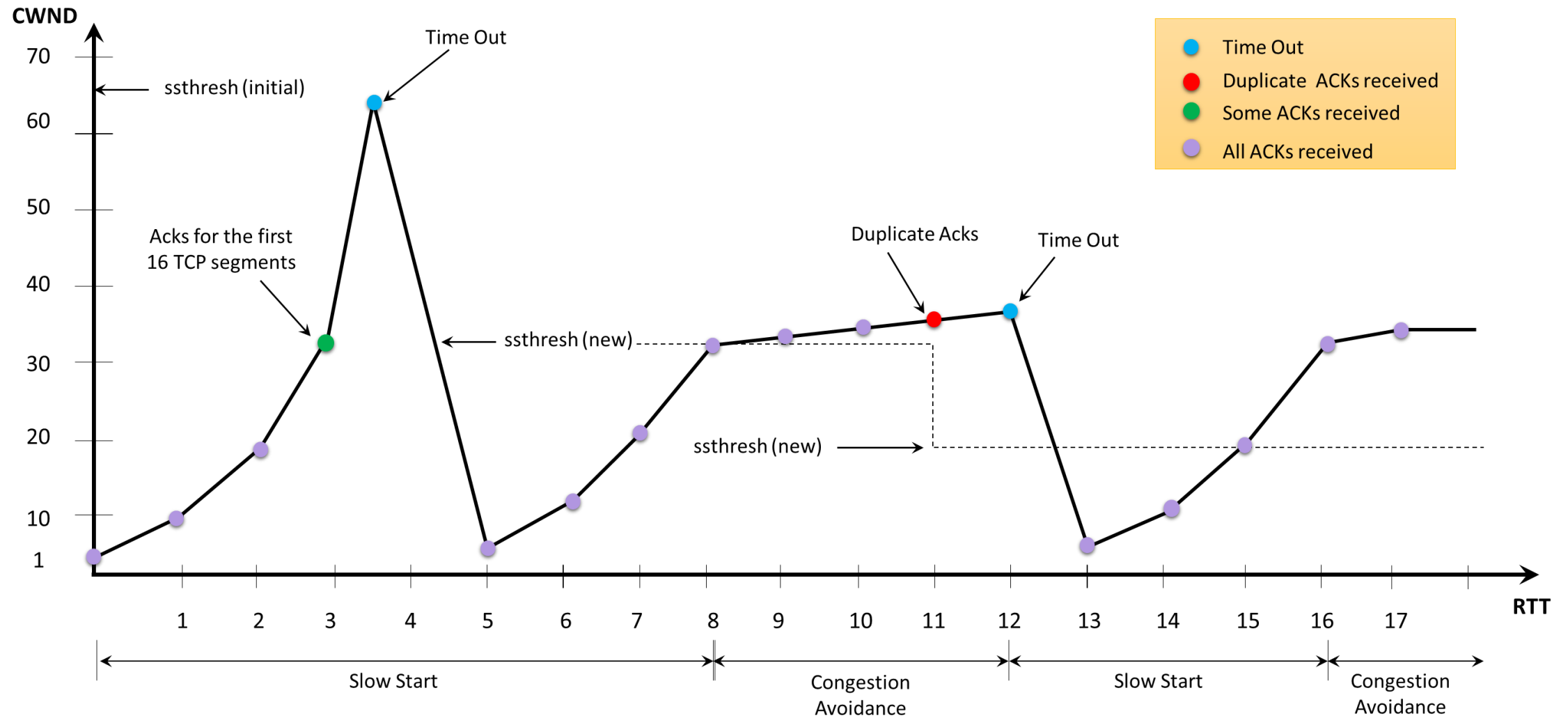
Step 3. Now Ready to Measure TCP Throughput



Step 3. Slow Start TCP Throughput Measurement



Step 3. TCP Throughput Equilibrium



Software Operation

ExpertTCP™

GL PacketExpert10GX

File View System Windows Help

Application: ExpertTCP

ExpertTCP

- Config
 - Remote
 - Interface-Local (Port1)
 - Interface-Remote(Port1)
 - Network Setup
 - TCP Setup
 - Test Setup**
- Results
 - Overall Status
 - Path MTU Results
 - Baseline RTT Results
 - Test Parameter Summary
 - Overall Results
 - RTT Results
 - Throughput Results
 - Statistics
 - Final Results
- Graph
 - Throughput
 - ThroughputVsRTT
 - ThroughputVsRetransmitted
- Port Statistics-Local (Port1)
- Port Statistics-Remote (Port1)
- Reports

Interface - Local (Port1)


Details

Hardware MAC address: 00-21-C2-00-2C-81

Settings

Interface Type: Electrical
Link Speed: 1000Mbps

Status

Link: 
Interface Type: Optical
Auto-Negotiation Status: -
Speed: 10 Gbps
Duplex Mode: Full Duplex
Flow Control: Enabled

Network Setup

Client (Local)

MAC Address: ☐ User Defined
00-21-c2-00-2c-81

IP Address: 192 . 168 . 1 . 111
Subnet Mask: 255 . 255 . 255 . 0
Default Gateway: 192 . 168 . 1 . 1

Network Under Test

Link Type: ☒ Symmetrical ☐ Asymmetrical
Upstream CIR: 1000.00 Mbps
Downstream CIR: 1000.00 Mbps




TCP Setup

No of TCP Connection: 16

TCP Port Configuration: ☒ Automatic ☐ Manual

| TCP Connection No. | Client Port | Server Port |
|--------------------|-------------|-------------|
| 1 | 5000 | 6000 |
| 2 | 5001 | 6001 |
| 3 | 5002 | 6002 |
| 4 | 5003 | 6003 |
| 5 | 5004 | 6004 |
| 6 | 5005 | 6005 |
| 7 | 5006 | 6006 |
| 8 | 5007 | 6007 |
| 9 | 5008 | 6008 |
| 10 | 5009 | 6009 |
| 11 | 5010 | 6010 |
| 12 | 5011 | 6011 |

Test Setup

Direction: ☒ Upstream  ☐ Downstream  ☐ Upstream and Downstream 

Transfer Size: 12500.000 MBytes

Test Selection

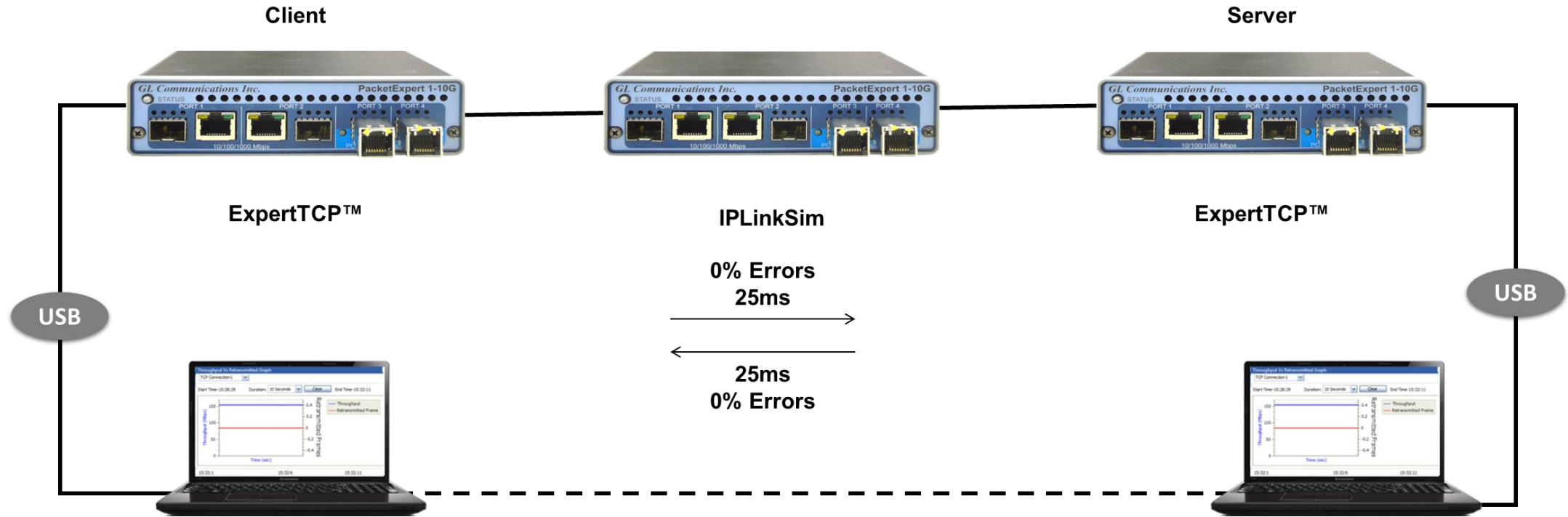
☒ Run Throughput Test
☒ Run Path MTU Test
☒ Run Baseline RTT Test

Upstream MTU: 850 Bytes
Downstream MTU: 850 Bytes
Upstream RTT: 0.056 msec
Downstream RTT: 0.056 msec

Start

Ready

Test Setup with Impairments



Network Setup

All settings configured locally on the client side.

Remote

Remote Server IP Address192 , 168 , 1 , 232Disconnect

StatusConnected

Interface - Local (Port1)

Details

Hardware MAC address00-21-C2-00-2C-81

Status

Link

Interface TypeOptical

Auto-Negotiation Status-

Speed10 Gbps

Duplex ModeFull Duplex

Flow ControlEnabled

Settings

Interface TypeOptical

Link Speed10000Mbps

Apply

Interface - Remote(Port1)

Details

Hardware MAC address00-21-C2-00-2D-11

Status

Link

Interface TypeOptical

Auto-Negotiation Status-

Speed10 Gbps

Duplex ModeFull Duplex

Flow ControlEnabled

Settings

Interface TypeOptical

Link Speed10000Mbps

Apply

Network Setup (Contd.)

Separate Upstream and Downstream bandwidths configurable for asymmetrical path

Network Setup

Client
(Local)

MAC Address
☐ User Defined
00-21-c2-00-2d-11

IP Address
IP Address 192 . 168 . 1 . 111
Subnet Mask 255 . 255 . 255 . 0
Default Gateway 192 . 168 . 1 . 1

Network
Under Test

Link Type
☒ Symmetrical ☐ Asymmetrical
Upstream CIR 1000.00 Mbps
Downstream CIR 1000.00 Mbps

Server
(Remote)

MAC Address
☐ User Defined
00-21-c2-00-22-e8

IP Address
IP Address 192 . 168 . 1 . 222
Subnet Mask 255 . 255 . 255 . 0
Default Gateway 192 . 168 . 1 . 1

TCP Setup

Single TCP connection

TCP Setup

No of TCP Connection

TCP Port Configuration ☒ Automatic ☐ Manual

| TCP Connection No. | Client Port | Server Port |
|--------------------|-------------|-------------|
| 1 | 5000 | 6000 |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |
| | | |

Multiple TCP connections

TCP Setup

No of TCP Connection

TCP Port Configuration ☒ Automatic ☐ Manual

| TCP Connection No. | Client Port | Server Port |
|--------------------|-------------|-------------|
| 1 | 5000 | 6000 |
| 2 | 5001 | 6001 |
| 3 | 5002 | 6002 |
| 4 | 5003 | 6003 |
| 5 | 5004 | 6004 |
| 6 | 5005 | 6005 |
| 7 | 5006 | 6006 |
| 8 | 5007 | 6007 |

TCP Setup (contd.)

The screenshot shows a 'Test Setup' window with the following configuration:

- Direction:** ☒ Upstream (indicated by a green up arrow), ☐ Downstream (indicated by a green down arrow), ☐ Upstream and Downstream (indicated by green up and down arrows).
- Transfer Size:** 12500.000 MBytes.
- Test Selection:**
 - ☒ Run Throughput Test
 - ☒ Run Path MTU Test
 - Upstream MTU: 850 Bytes
 - Downstream MTU: 850 Bytes
 - ☒ Run Baseline RTT Test
 - Upstream RTT: 0.056 msec
 - Downstream RTT: 0.056 msec

- Upstream/Downstream/Bidirectional
- Path MTU - run test and discover or user can enter manually
- Baseline RTT - run test and find out or user can enter manually
- Separate Path MTU/Baseline RTT configuration for Upstream/Downstream directions for asymmetrical paths

Status and Results

Overall Status

Test Status

Done

Current Direction

-

Current Test

| Test | Status | Result |
|-------------------------|--------|--------|
| Path MTU (Upstream) | | |
| Baseline RTT (Upstream) | | |
| Throughput (Upstream) | | |
| | | |
| | | |
| | | |
| | | |

TCP Connection Status:

| Connection No. | Source Port | Destination Port | Status |
|----------------|-------------|------------------|-------------------|
| 0 | 5000 | 6000 | Connection Closed |
| | | | |
| | | | |
| | | | |
| | | | |

Path MTU results

Upstream

Downstream

Path MTU

1500

Bytes

Baseline RTT Results

Upstream

Downstream

Trial Duration

91

Average RTT

50.018

msec

Minimum RTT

50.015

msec

Maximum RTT

50.040

msec

Baseline RTT Value Selected

50.015

msec

Test Parameter Summary

Upstream

Downstream

Baseline RTT

50.015

msec

Calculated BDP

625.190

KBytes

TCP Window

65535

Bytes

Path MTU

1500

Bytes

MSS Used

1448

Bytes

No of TCP Connection

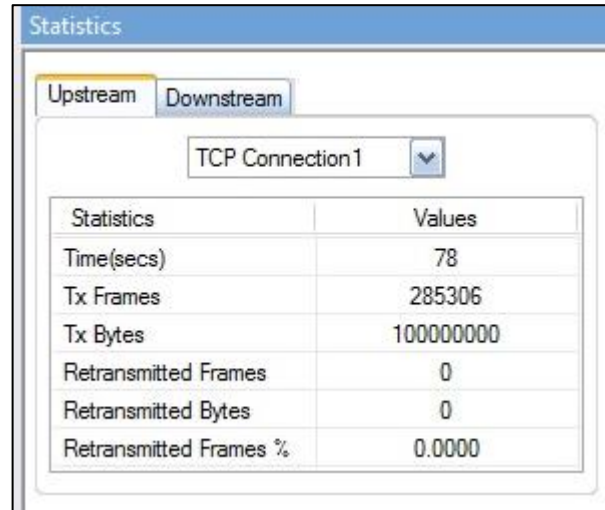
1

Transfer Size

100.000

MBytes

Statistics and Periodic Results



Statistics

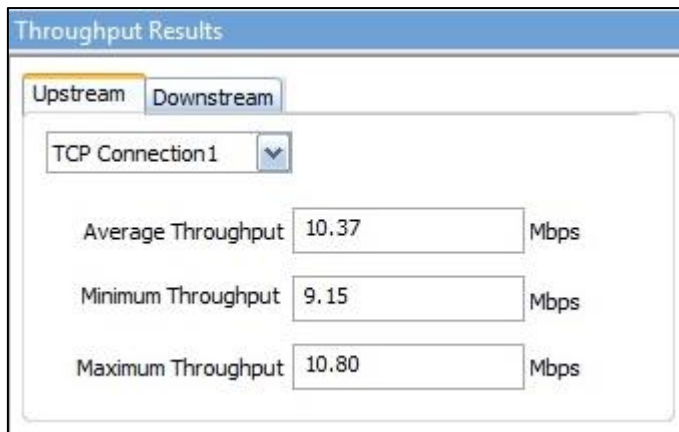
Upstream Downstream

TCP Connection 1

| Statistics | Values |
|------------------------|-----------|
| Time(secs) | 78 |
| Tx Frames | 285306 |
| Tx Bytes | 100000000 |
| Retransmitted Frames | 0 |
| Retransmitted Bytes | 0 |
| Retransmitted Frames % | 0.0000 |

Statistics are updated every second and includes -

- TCP Transmitted Frames/Bytes
- TCP Retransmitted Frames/Bytes
- Retransmitted Bytes Percentage

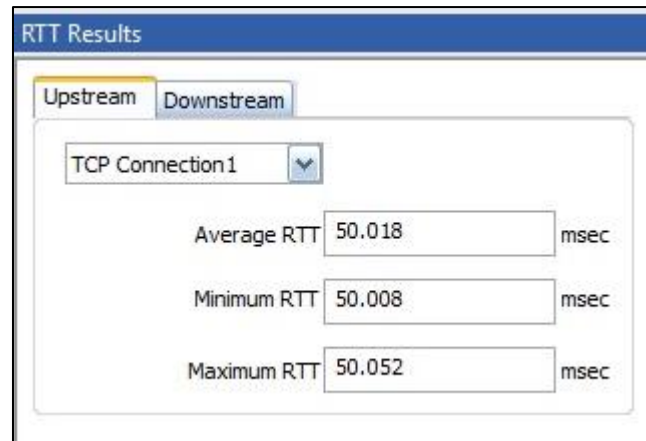


Throughput Results

Upstream Downstream

TCP Connection 1

| | | |
|--------------------|-------|------|
| Average Throughput | 10.37 | Mbps |
| Minimum Throughput | 9.15 | Mbps |
| Maximum Throughput | 10.80 | Mbps |



RTT Results

Upstream Downstream

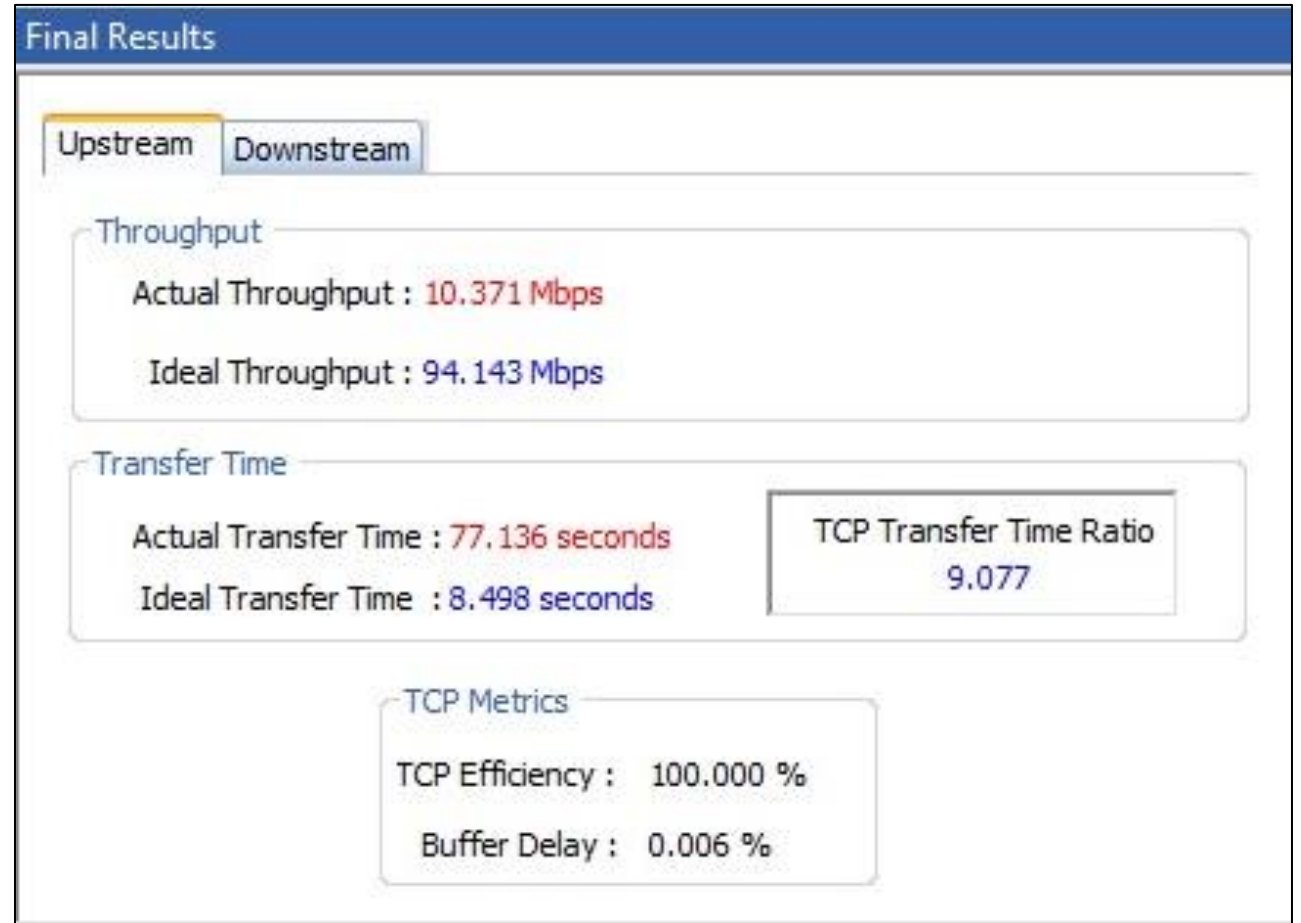
TCP Connection 1

| | | |
|-------------|--------|------|
| Average RTT | 50.018 | msec |
| Minimum RTT | 50.008 | msec |
| Maximum RTT | 50.052 | msec |

Throughput and RTT values are calculated every second and displayed. Minimum, Maximum and Average Values are displayed

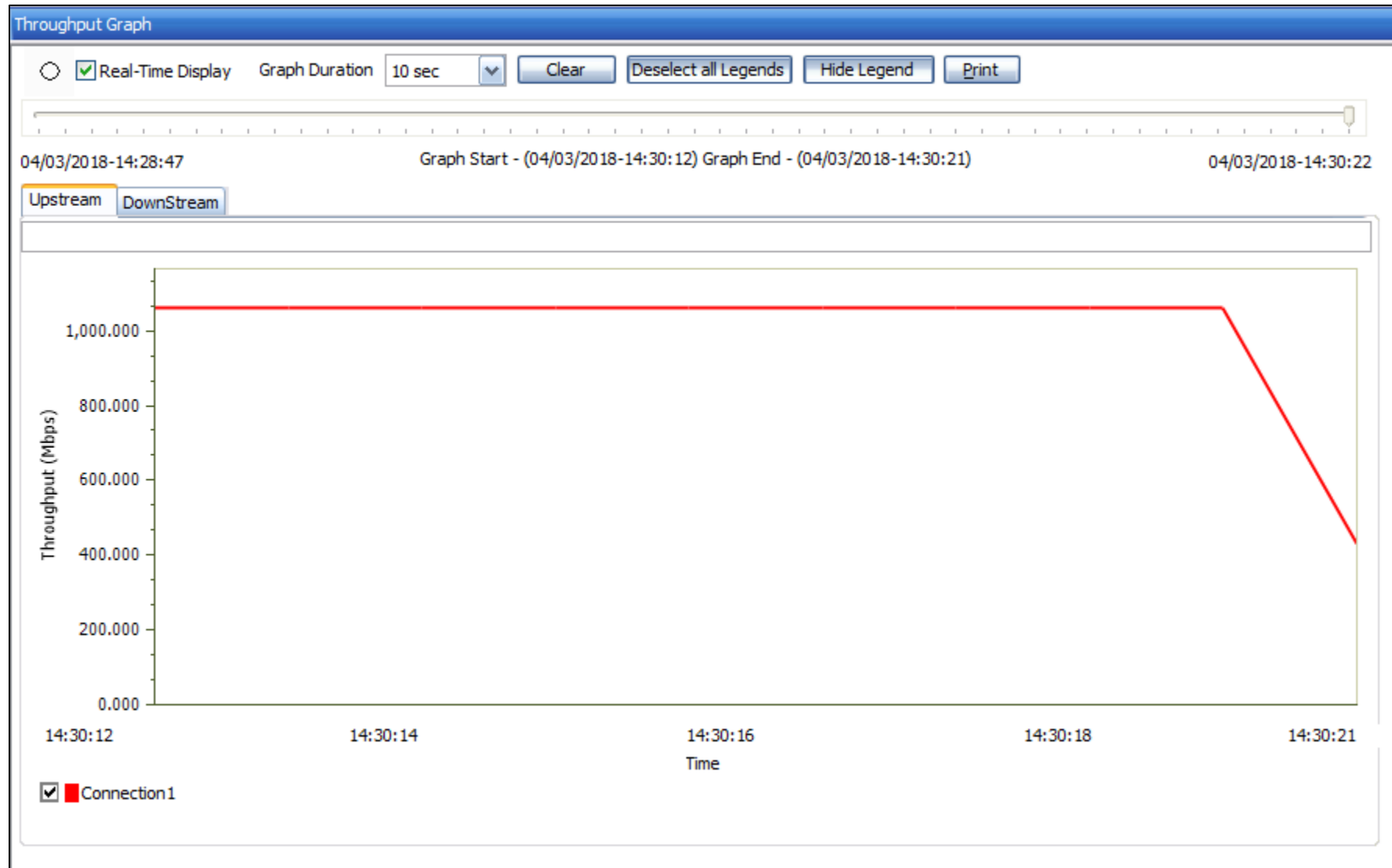
Final Results

- **Ideal Throughput** - the maximum possible TCP throughput for the given CIR
- **Ideal Transfer Time** - the time taken to transfer the test data size at the ideal throughput
- **TCP Transfer Time Ratio** - Measure of how much Actual transfer time is greater than the Ideal transfer time
- **TCP Efficiency** - measure of the number of Transmitted bytes compared to the retransmitted bytes
- **Buffer Delay** - measure of how much the RTT increases during the actual TCP Throughput test compared to the Baseline RTT



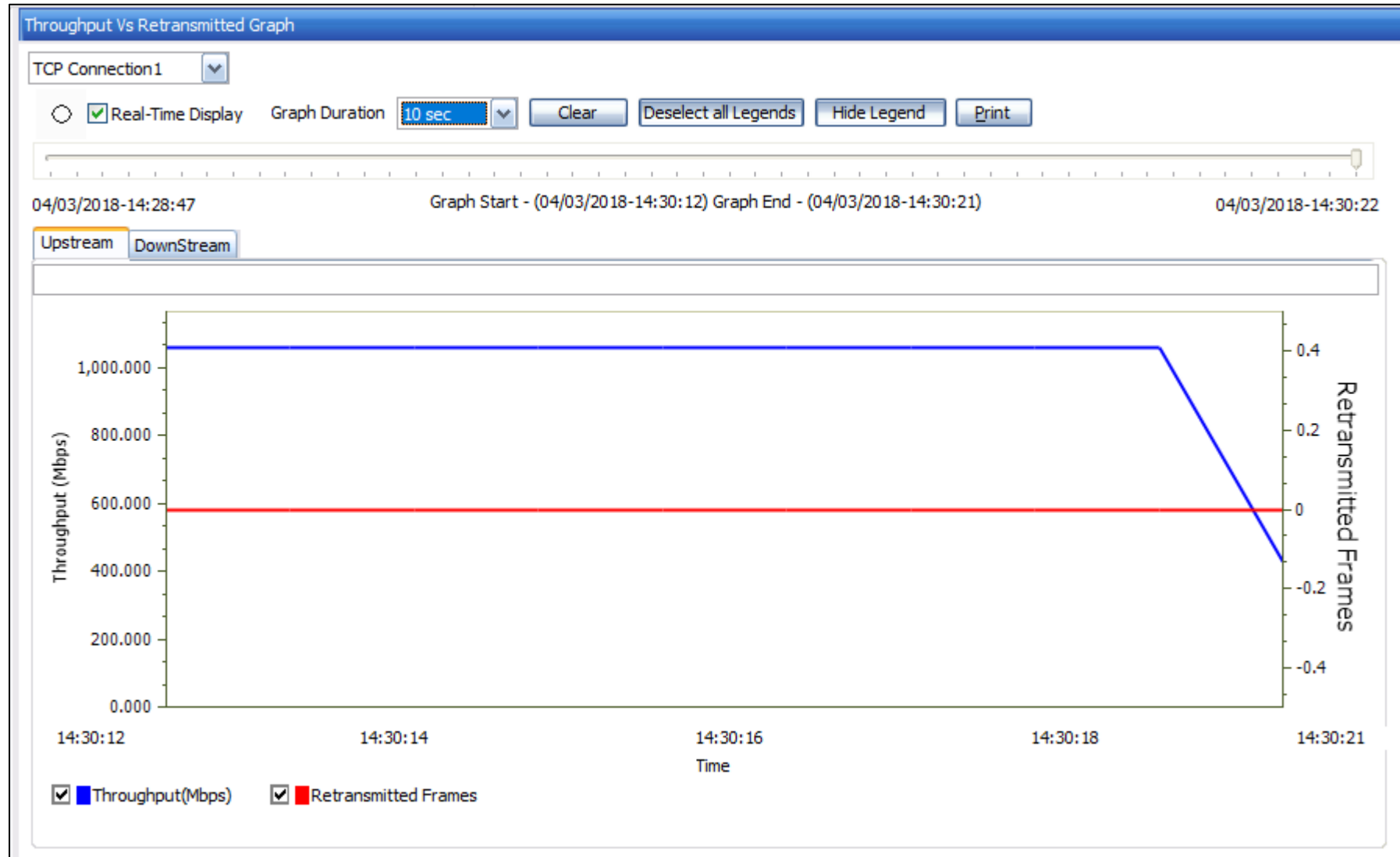
Throughput Graph

With 0.1% Packet Loss



Throughput vs. Retransmitted Frames Graph

With 0.1% Packet Loss



Multiple TCP connections

With 8 TCP connections

Test Parameter Summary

Upstream Downstream

| | | |
|----------------------|---------|--------|
| Baseline RTT | 50.022 | msec |
| Calculated BDP | 625.274 | KBytes |
| TCP Window | 524280 | Bytes |
| Path MTU | 1500 | Bytes |
| MSS Used | 1448 | Bytes |
| No of TCP Connection | 8 | |
| Transfer Size | 100.000 | MBytes |

TCP window of 5,24,280 bytes shared among 8 connections

Thank You