International Journal of Communication Networks and Information Security (IJCNIS) Vol. 4, No. 2, August 2012

Performance Analysis of IPv6 Transition Mechanisms over MPLS

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Abstract: Exhaustion of current version of Internet Protocol version 4 (IPv4) addresses initiated development of next-generation Internet Protocol version 6 (IPv6). IPv6 is acknowledged to provide more address space, better address design, and greater security; however, IPv6 and IPv4 are not fully compatible. For the two protocols to coexist, various IPv6 transition mechanisms have been developed.

This research will analyze a series of IPv6 transition mechanisms over the Multiprotocol Label Switching (MPLS) backbone using a simulation tool (OPNET) and will evaluate and compare their performances. The analysis will include comparing the end-to-end delay, jitter, and throughput performance metrics using tunneling mechanisms, specifically Manual Tunnel, Generic Routing Encapsulation (GRE) Tunnel, Automatic IPv4-Compatible Tunnel, and 6to4 Tunnel between Customer Edge (CE)-to-CE routers and between Provider Edge (PE)-to-PE routers. The results are then compared against 6PE, Native IPv6, and Dual Stack, all using the MPLS backbone. The traffic generated for this comparison are database access, email, File Transfer, File Print, Telnet, Video Conferencing over IP, Voice over IP, Web Browsing, and Remote Login. A statistical analysis is performed to compare the performance metrics of these mechanisms to evaluate any statistically-significant differences among them. The main objective of this research is to rank the aforementioned IPv6 transition mechanism and identify the superior mechanism(s) that offer lowest delay, lowest jitter, and highest throughput.

Keywords: IPv6, 6to4 Tunnel, GRE Tunnel, Automatic IPv4-Compatible Tunnel, Manual Tunnel, 6PE, Dual Stack, Native IPv6, Performance Analysis

1. Introduction

The current version of Internet Protocol, IPv4 is widely used. It is easy to implement, robust, and supports a wide range of applications. However, the growth of the Internet and address-hungry Internet services and applications have depleted the IPv4 addresses. As more devices require connectivity to the Internet, IPv4 addresses will not be able to address this increased demand. IPv6 is the next-generation Internet Protocol that offers more IP addresses and overcomes the address exhaustion of IPv4. For latecomers to the Internet explosion, IPv6 is their only solution. Therefore IPv6 is expected to be widely used. The transition between IPv4 and IPv6 will be a long process because the two protocols are not backward compatible [9]. It is impossible to switch the entire internet over to IPv6 overnight. Because IPv4 and IPv6 will coexist for a long time, it is critical that the transition mechanisms are evaluated, specifically the ones over widely-used MPLS network.

MPLS is a packet labeling and forwarding technology that is highly scalable and widely used by the service providers and enterprises in their existing IPv4 backbones. MPLS protocol inspects the labels and forwards packets based on the content of the label, rather than by performing complex routing lookups and examining the packets. Enterprises use the MPLS backbone to connect remote offices and headquarters to each other. The service providers and enterprises using MPLS networks may view the integration of IPv6 services over an MPLS infrastructure as a normal evolution. The MPLS backbone provides the capability to connect islands of IPv6 with each other, either by using the existing IPv4 MPLS backbone or by partially or fully upgrading the MPLS backbone.

In the event that the existing IPv4 MPLS backbone has to be used, there are multiple methods to provide connectivity to islands of IPv6 [2], [18]. Because the cost of fully or partially upgrading the backbone is high and requires upgrading the network, transition mechanisms have been developed. Below are different methods evaluated in this paper that leverage existing IPv4 MPLS network and add IPv6 services without requiring changes to the backbone. These methods enable isolated IPv6 domains to communicate with each other over the existing IPv4 MPLS backbone. These approaches can be taken to avoid fully upgrading the MPLS backbone, resulting in lower operational cost and risk.

- IPv6 using tunnels between CE-to-CE routers, including Manual Tunnel, GRE Tunnel, Automatic IPv4-Compatible Tunnel, and 6to4 Tunnel
- IPv6 using tunnels between PE-to-PE routers, including Manual Tunnel, GRE Tunnel, Automatic IPv4-Compatible Tunnel, and 6to4 Tunnel
- IPv6 Provider Edge Routers (6PE)

This paper also evaluates other methods of introducing IPv6 that require changes to the MPLS backbone. Dual Stack and Native IPv6 are the two methods evaluated in this paper which introduces higher operational cost due to upgrade of the MPLS backbone.

Performance metrics, such as delay, jitter, and throughput, of these methods are analyzed in this paper and statistical analysis is performed.

The main purpose of this research is to rank the aforementioned IPv6 transition mechanisms and identify the superior mechanisms that offer lowest delay, lowest jitter, and highest throughput. To achieve this, the objectives below are identified and evaluated.

Objective 1

Generate data and perform statistical analysis to determine if there is a statistically-significant difference among the performance metrics (delay, jitter, throughput) of **IPv6 CE-to-CE tunneling mechanisms**, specifically Manual Tunnel, GRE Tunnel, Automatic IPv4-Compatible Tunnel, and 6to4 Tunnel. Then evaluate which method(s) are superior for each performance metric.

Objective 2

Generate data and perform statistical analysis to determine if there is a statistically-significant difference among the performance metrics (delay, jitter, throughput) of **IPv6 PE-to-PE tunneling mechanisms**, specifically Manual Tunnel, GRE Tunnel, Automatic IPv4-Compatible Tunnel and 6to4 Tunnel. Then evaluate which method(s) are superior for each performance metric.

Objective 3

Generate data and perform statistical analysis to determine if there is a statistically-significant difference among the performance metrics (delay, jitter, throughput) of **IPv6 PE-to-PE and IPv6 CE-to-CE tunneling mechanisms**. Then evaluate which method(s) are superior for each performance metric.

Objective 4

Generate data and perform statistical analysis to determine if there is a statistically-significant difference among the performance metrics (delay, jitter, throughput) of **6PE, Dual Stack, Native IPv6, and best tunneling mechanism**. Then evaluate which method(s) are superior for each performance metric.

Objective 5

Perform statistical analysis to determine the **overall performance metrics ranking of all the aforementioned transition mechanisms** in the order of best to worst transition mechanism that offer lowest delay, lowest jitter, and highest throughput.

This research consists of four steps. Figure 1 demonstrates these steps and the methodology used to assess the research objectives.

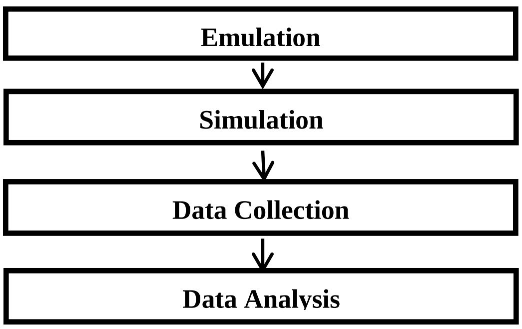

Figure 1. Research Methodology

The emulation was done using the GNS3 tool, and the simulation and data collection was done using the OPNET Modeling and Simulation tool. The data analysis was done using statistical analysis methods leveraging Excel 2010.

Section 2 describes the related research. Section 3 describes the experiment setup, including emulation, simulation, and data collection processes. Section 4 describes the data analysis in great detail. Section 5 and Section 6 describe the results and conclusion and future work, respectively.

2. Related Research

IPv6 transition mechanisms are widely researched. Listed below are a few samples of the researches that have been conducted. In [22] packet delay and loss of IPv4 and IPv6 in 600 paths over time is measured. In [20] performance issues on aviation applications among three domains using IPv6-in-IPv4 static tunnel is researched. In [5] the IPv6 and IPv4 roundtrip delays from two locations are measured and the IPv6 problem in the Dual stack environment is identified.

In [14] and [15] the network performance such as throughput, delay, jitter, and CPU usage of IPv4-v6 Configured Tunnel and 6to4 Transition mechanisms on Linux operating systems and on Windows server operating systems are evaluated.

In [19] the Dual stack, tunneling, and translation mechanisms overview is presented as well as technical issues related to IPv6 deployment. In [1] the performance of IPv6 tunneled traffic of Teredo and ISATAP in the test bed on Microsoft Windows and Linux operating systems are compared. Audio streaming, video streaming, and ICMP ping traffic was run for this evaluation.

In [12] the empirical performance of IPv6 versus IPv4 under Dual Stack for Round Trip Time, throughput, operating system dependencies, and address configuration latency is evaluated.

In [4] the simulation of IPv4-to-IPv6 Dual Stack Transition Mechanisms (DSTM) between IPv4 hosts in an integrated IPv6/IPv4 network is evaluated. A comparative study of the behavior of an IPv4-only network with that of DSTM under various types of traffic patterns considering end-to-end delay is presented.

In [9] an examination of IPv4 and IPv6 networks by discussing constraints, various techniques, and standards required for high-level compatibility, smooth transition, and interoperation between IPv4 and IPv6 is presented.

In [2] the IPv4/IPv6 transition technologies and Univer6 Architecture are discussed. The paper summarizes and compares translation methods, tunneling methods, and security problems, then presents Univer6 architecture for the future IPv6 transition.

Research has also been done in the area of Mobile IPv6 such as [17], which compares Mobile IPv6, Hierarchical, Fast Handovers Mobile IPv6, and their combination.

Although a great amount of research in this area has been done, to the best of our knowledge no one has performed a study on all the mechanisms identified in this paper over an MPLS network. Additionally, no research included the statistical analysis evaluating the performance impact over a long period of time with large data points. Moreover, this study is generating data with a large number of applications such as Database Access, Email, File Transfer, File Print, Telnet, Video Conferencing over IP, Voice over IP, Web Browsing, and Remote Login. Since OPNET at the time of this research did not support ISATAP, Teredo, and 6VPE, these mechanisms are not included in this study.

3. Experiment Setup

The OPNET simulation tool was used with the following specifications. The CE routers were set as Cisco 3600 routers, the PE routers and the P (Provider) routers were set as Cisco 7200 routers, and the switches were set as Cisco 2940s. These routers were first configured in an emulated environment (GNS3) with IOS release 12.4(25) with the configuration described below. Then the configuration for all the scenarios was imported to the OPNET Modeling and Simulation tool, OPNET SP Guru Network Planner 16.0.

The MPLS cloud was configured with PE routers to have External Border Gateway Protocol (EBGP) for connectivity to CE routers and Multiprotocol Border Gateway Protocol (MP-BGP) protocol for connectivity to the remote PE router. The Interior Gateway Protocol (IGP) routing protocol inside the MPLS cloud is Open Shortest Path First (OSPF). The appropriate redistributions were configured and the suitable address family was configured for IPv4 and/or IPv6 depending on the transition mechanism.

The MPLS cloud was then configured to be IPv4-enabled and the clients and servers are IPv6-enabled for the tunneling transition mechanisms [18], [21]. If the clients on each IPv6 island need to communicate with servers at different islands they have to traverse the IPv4 MPLS cloud. The various tunneling mechanisms shown in Figure 2 were then configured with a total of eight tunneling scenarios. Four tunneling mechanisms – Manual Tunnel, Automatic IPv4-Compatible Tunnel, GRE Tunnel, and 6to4 Tunnel – were configured between CE-to-CE routers, and the other four were configured between PE-to-PE routers. In the case of CE-to-CE tunneling, the CEs were configured to be IPv4 and IPv6-enabled and the PEs and P routers were configured to be IPv4 only. In the case of PE-to-PE tunneling, the CEs were configured to be IPv6 only, the PE routers were configured to be IPv4 and IPv6-enabled, and the P router was configured for IPv4 only. All the clients and servers are configured to be IPv6-enabled.

These tunneling mechanisms were used to carry IPv6 traffic over the existing IPv4 network by encapsulating IPv6 packets in the IPv4 header. At the tunnel end node, the packet is decapsulated and the IPv4 packet header is stripped. Then the original IPv6 packet is routed to its final IPv6 destination. The tunnels are either manually or automatically configured, as described below.

- Manual Tunnel or Manually-Configured Tunnel mechanism builds a permanent virtual link between two IPv6 networks that are connected over an IPv4 backbone. It is a point-to-point static tunnel. The start and end points of the tunnel have IPv4-routable addresses and an IPv6 address is configured on the tunnel interface. The addresses in the tunneled IPv6 packets do not provide the IPv4 address of the tunnel end point. Instead, the router performing the tunneling provides configuration information that determines the tunnel end point address [8], [16].
- GRE Tunnel or Manual GRE Tunnel mechanism [6] is a type of manual tunnel with both tunnel source and destination configured manually for GRE. The start and end points of the tunnel have IPv4-routable addresses and an IPv6 address is configured on the tunnel interface. The addresses in the tunneled IPv6 packets do not provide the IPv4 address of the tunnel end point. This tunnel has an extra encapsulation header for the GRE header. Therefore, within the IPv4 backbone the tunnel will have an IPv6 packet encapsulated into the GRE header and IPv4 header. GRE tunnels are also point-to-point tunnels.
- Automatic IPv4-Compatible Tunnel mechanism [8] has no preconfigured tunnels and the node performing the tunneling is assigned IPv4-compatible IPv6 addresses. The destination address is assigned automatically from the embedded IPv4 address of the IPv6 next-hop for the IPv6 route.
- 6to4 Tunnel mechanism [3] is implemented almost entirely in border routers, without specific host modifications except a suggested address selection default. 6to4 is an automatic tunnel where the tunnel termination is not explicitly configured and is obtained dynamically from the IPv4 address embedded in the destination IPv6 address of the packet. The IPv6 address of the tunnel interface starts with 2002: and the next 32 bits are the IPv4 address. This tunneling mechanism, unlike the manual tunnel, is not point-to-point and supports point-to-multipoint.

Next, the 6PE, Native IPv6, and Dual Stack transition mechanisms were configured. The MPLS cloud is IPv4-enabled in the case of 6PE with PE routers supporting both IPv4 and IPv6, the CE routers supporting IPv6, and the P router supporting IPv4 only. In the 6PE transition mechanism, the MPLS core infrastructure is IPv6-unaware and only the PE routers are updated to support IPv4/IPv6 and 6PE. The 6PE routers exchange the IPv6 reachability information transparently over the core using the MP-BGP over IPv4. In doing so, the BGP Next Hop field is used to convey the IPv4 address of the 6PE router so that dynamically-established IPv4-signaled MPLS Label Switched Paths (LSP) can be used without explicit tunnel configuration [7]. The 6PE forwarding uses labels instead of IP headers. It has two labels; the inner label is limited to the advertised destination IPv6 prefix, and the outer label is related to the egress IPv4 address of the 6PE router. The IPv6 reachability is between the 6PE devices using MP-BGP.
For Native IPv6, the MPLS cloud and all the devices were configured to be IPv6-enabled only. For Dual Stack, all devices were configured to be IPv4/IPv6-enabled on all interfaces. Figure 3 demonstrates the 6PE, Dual Stack, and Native IPv6 transition mechanism setup.

The clients and servers are Windows XP and Solaris 2.9. The Maximum Transmission Unit (MTU) is set to 1500 on all interfaces. The Maximum Segment Size is set to auto-detect to adjust for tunnel headers of each mechanism. The OPNET network setup is shown in figure 4 above.

Traffic is generated using Database Access, Email, File Transfer, File Print, Telnet, Video Conferencing over IP, Voice over IP, Web Browsing, and Remote Login applications via OPNET application attribute.

Next, the OPNET profile attribute such as Operation Mode, Start Time, Duration, and Repeatability are configured for each application. These variables are identical for all scenarios.

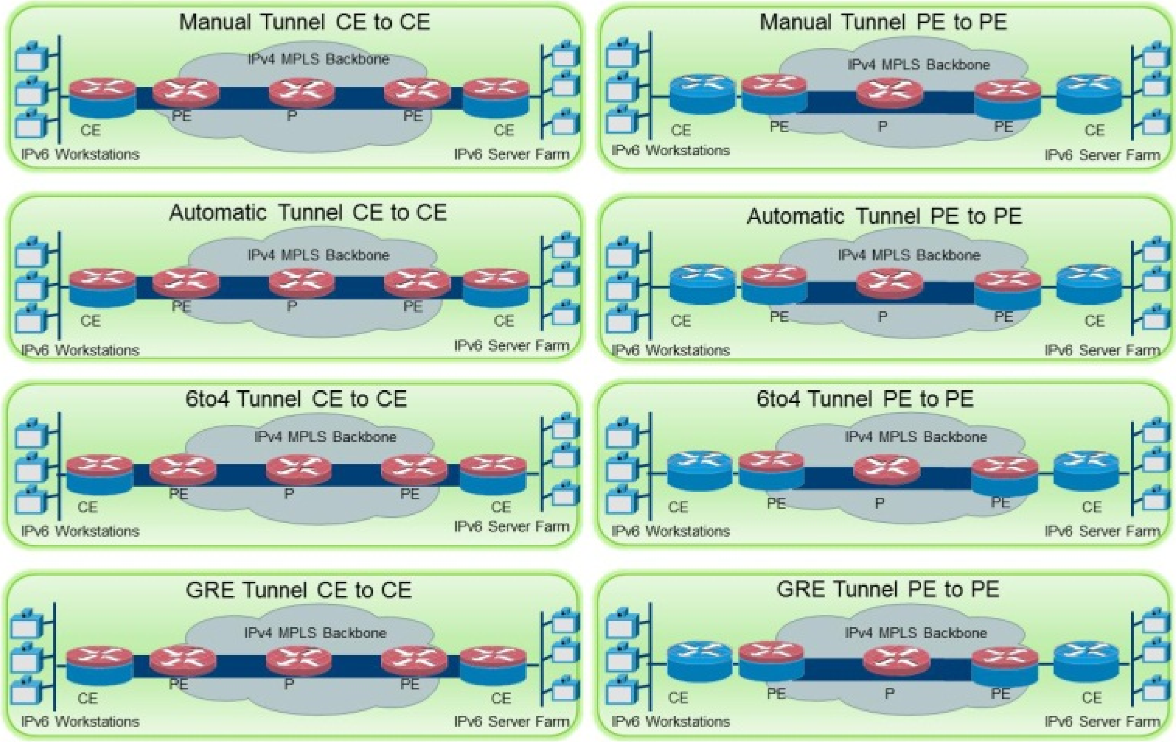

Figure 2. CE-to-CE and PE-to-PE IPv6 Tunneling Mechanisms

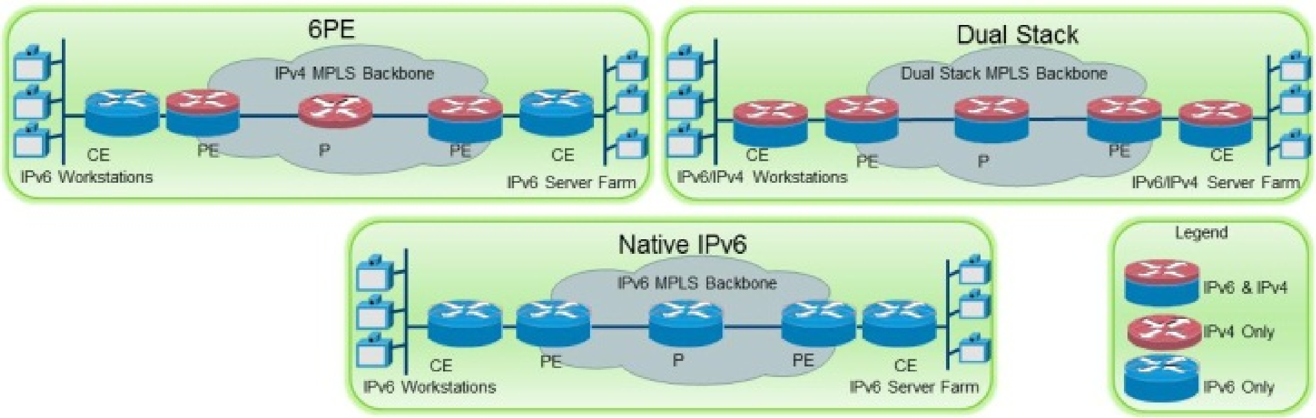

Figure 3. 6PE, Dual Stack, and Native IPv6 Transition Mechanisms

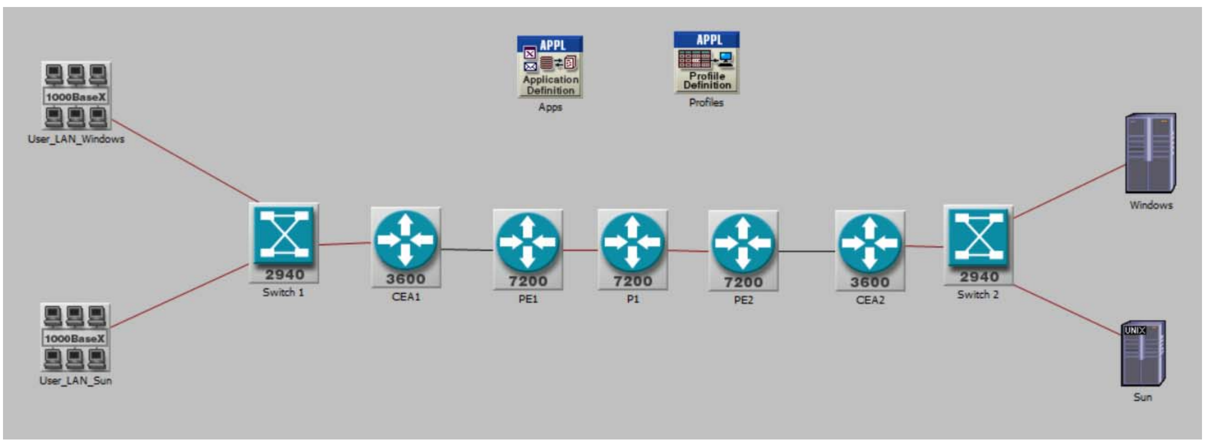

Figure 4. OPNET Network Setup

The model was then run with three seeds, each 5 simulation hours long for each of 11 scenarios. The metrics were set to be collected every second, resulting in 18,000 values per statistic for each seed. As a result, each scenario collected 54,000 values for each performance metric.

Figures 5, 6 and 7 demonstrate the average end to end delay, average end to end jitter and average throughput respectively with seeds for all scenarios for the duration of 5 simulation hours.

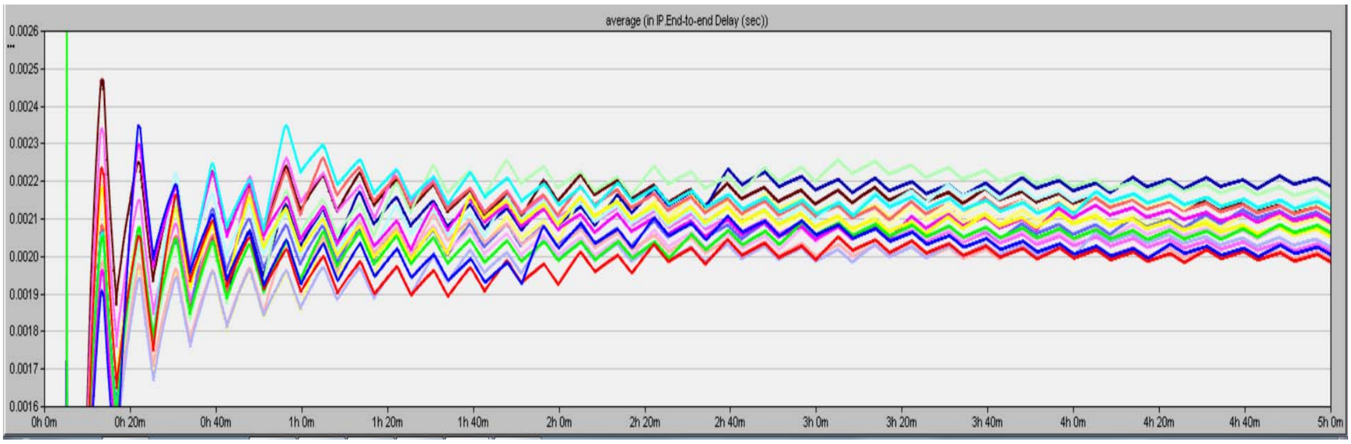

Figure 5. OPNET Average End-to-End Delay for All Scenarios

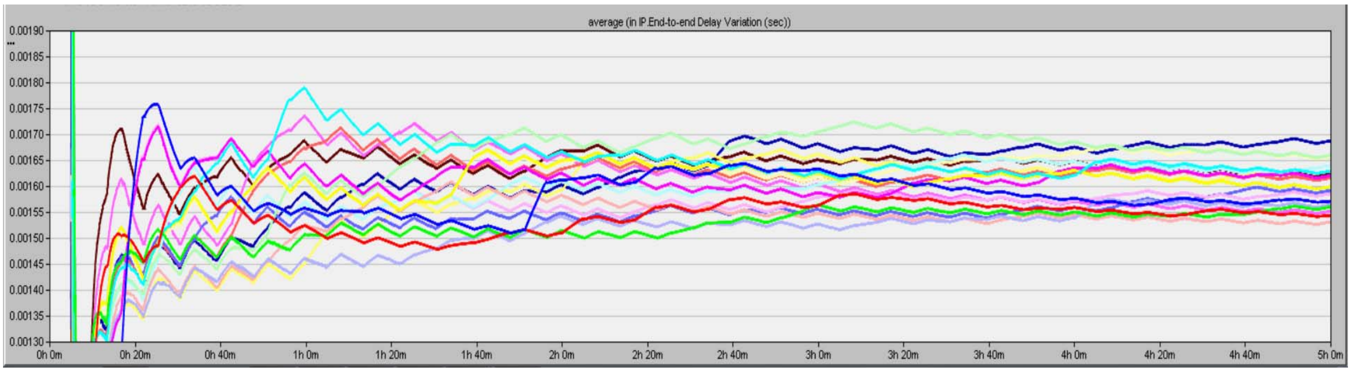

Figure 6. OPNET Average End-to-End Jitter for All Scenarios

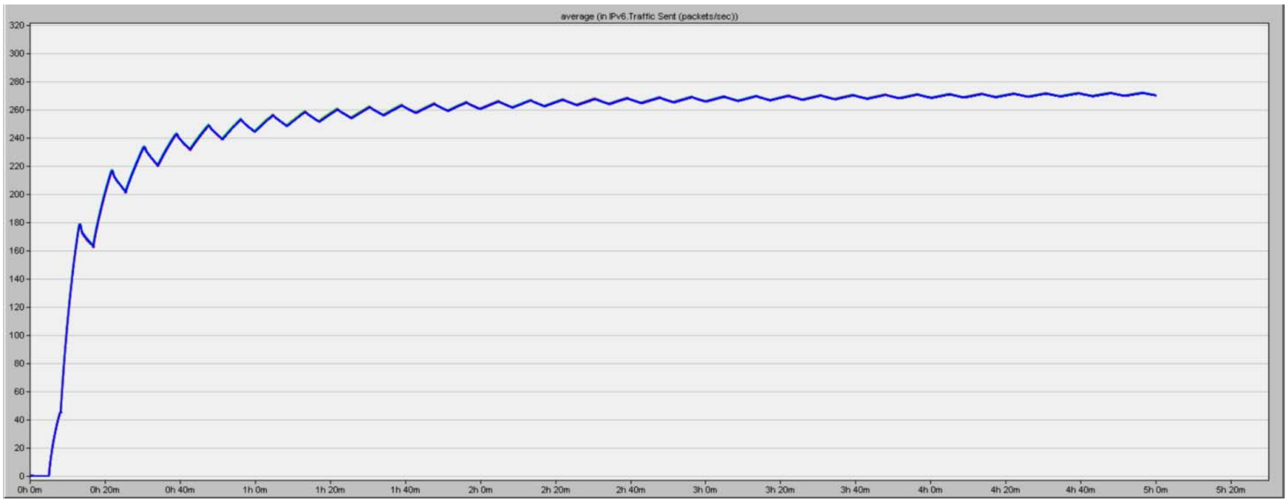

Figure 7. OPNET Average Throughput for All Scenarios

As shown in the figures above, the 54,000 values collected for each performance metric are extremely large and the numbers are close to each other. As a result, the statistical analysis is performed to identify if there are any statistically-significant differences among the mechanisms for each performance metric. Section 4 describes the statistical analysis performed to evaluate the collected data.

4. Analysis

This section describes the analysis performed to evaluate the collected data. Methods below were used to perform the statistical analysis [11], [13]:

- Analysis of Variance (ANOVA)
- Scheffe's method
- F-Test
- T-Test

ANOVA was used to determine if there is a statistically-significant difference in means among the scenarios. Scheffe's method was used to compare the means of each scenario. F-Test was used to demonstrate if the variances are equal. Finally, either Two Sample T-Test or T-Test using Y

degree of freedom was used to determine if the mean of one mechanism is different from the mean of the other.

4.1. *Analysis of Objective 1*

To determine if there are statistically-significant differences among the performance metrics (delay, jitter, throughput) of IPv6 **CE-to-CE tunneling mechanisms** and if so to determine which one is the superior method, the formulas below were used to accept or reject the hypothesis. Delay was analyzed first, followed by jitter and throughput.

4.1.1. *Delay*

The analysis of delay is described below [10].

ANOVA:

The hypothesis below was identified for ANOVA.

- Null Hypothesis (H0): Delay means are equal for CE-to-CE Tunneling mechanisms
- Alternative Hypothesis (H1): At least one delay mean for CE-to-CE Tunneling mechanism is different from other means

Following formulas below:

$$S_B^2 = \frac{\sum n_i \left(\bar{X}_i - \bar{X}_j\right)^2}{K-1} \quad (1)$$

$$S_w^2 = \frac{\sum (n_i - 1) S_i^2}{\sum (n_i - 1)} \quad (2)$$

$$F_{test} = \frac{S_B^2}{S_w^2} \quad (3)$$

$$F_{cv} = F_{\alpha,(k-1),(N-k)} \quad (4)$$

Where $\bar{X}_i$ and $\bar{X}_j$ are the means and S_i^2 and S_j^2 are the variances of the samples of sizes n_i and n_j respectively. The S_B^2 is variance among groups, S_W^2 is the variance within groups, F_{test} is the test value, F_{cv} is the critical value, and K is the number of scenarios.

The results for delay performance metrics are shown in Table 1. Since $F_{test} > F_{cv}$ the Null Hypothesis is rejected and there is enough evidence to demonstrate that at least one delay mean is different from other delay means among the four scenarios.

Table 1. ANOVA Results for Delay of CE-to-CE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Manual CE	51753	108.5816448	0.002098074	2.44595E-06
Auto CE	51864	108.5054418	0.002092115	2.44083E-06
GRE CE	51858	111.5912296	0.002151861	2.5934E-06
6to4 CE	51892	110.724942	0.002133757	2.53934E-06

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	0.000127451	3	4.24835E-05	16.96009107	5.2E-11	2.604952
Within Groups	0.519426123	207363	2.50491E-06			
Total	0.519553573	207366				

Scheffe's Method:

Scheffe's method [13] using formulas and Table 2 demonstrates that there is a statistically-significant difference between delay means of the mechanisms where $F_s > F_c$. F_s is the test value and F_c is the critical value. The formulas used are:

$$S_w^2 = \frac{\sum (n_i - 1) S_i^2}{\sum (n_i - 1)} \quad (5)$$

$$F_s = \frac{\left(\bar{X}_i - \bar{X}_j\right)^2}{S_w^2 \left(\frac{1}{n_i} + \frac{1}{n_j}\right)} \quad (6)$$

Table 2. Scheffe Results for Delay of CE-to-CE Tunnel

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
Auto CE vs. Manual CE	0.367293934	7.812	No
Auto CE vs. 6to4 CE	17.95715863	7.812	Yes
Auto CE vs. GRE CE	36.95260966	7.812	Yes
Manual CE vs. 6to4 CE	13.17100779	7.812	Yes
Manual CE vs. GRE CE	29.91629276	7.812	Yes
6to4 CE vs. GRE CE	8.393773702	7.812	Yes

F-Test:

Next the F-Test [13] was used to evaluate if variances are equal using the hypothesis below:

- Null Hypothesis (H0): delay variance i = delay variance j
- Alternative Hypothesis (H1): delay variance i < delay variance j

The formula below illustrates the test statistics F_0, which is the ratio of the sample variances.

$$F_0 = \frac{S_i^2}{S_j^2} \quad (7)$$

The results shown in Table 3 were obtained. Since $F_0 >$ Fα, n_1-1, n_2-1 is not true then the Null Hypothesis is not rejected and there is enough evidence to support that delay variances are equal. Therefore the Two Sample T-Test is used to find which delay mean is less than the others.

Table 3. F-Test Results for Delay of CE-to-CE Tunnel

F-Test			
Transition Mechanism	Fα, n_1-1, n_2-1	F0	Test if F_0 > Fα, n_1-1, n_2-1
Auto CE vs. 6to4 CE	1	0.961206147	No
Auto CE vs. GRE CE	1	0.941170553	No
Manual CE vs. 6to4 CE	1	0.963220584	No
Manual CE vs. GRE CE	1	0.943143	No
6to4 CE vs. GRE CE	1	0.979155778	No

Two Sample T-Test:

Next the Two Sample T-Test [13] was evaluated using the hypothesis below:

- Null Hypothesis (H0): delay mean i = delay mean j
- Alternative Hypothesis (H1): delay mean i < delay mean j

The following formulas show t_0, the test statistics and S_p^2, the estimate of common variance:

$$t_0 = \frac{\bar{X}_i - \bar{X}_j}{S_p\sqrt{\frac{1}{n_i}+\frac{1}{n_j}}} \quad (8)$$

$$S_p = \sqrt{\frac{(n_i - 1)S_i^2 + (n_j - 1)S_j^2}{n_i + n_j - 2}} \quad (9)$$

The results shown in Table 4 were obtained.

Table 4. T-Test Results for Delay of CE-to-CE Tunnel

Two Sample T-Test			
Transition Mechanism	t_{α}, $n_1 + n_2$-2	t0	Test if $t_0 < -t_{\alpha}$, $n_1 + n_2$-2
Auto CE vs. 6to4 CE	1.64	-4.25017473	Yes
Auto CE vs. GRE CE	1.64	-6.064119396	Yes
Manual CE vs. 6to4 CE	1.64	-3.638063334	Yes
Manual CE vs. GRE CE	1.64	-5.453454824	Yes
6to4 CE vs. GRE CE	1.64	-1.820066369	Yes

Since t0 < $-t_{\alpha}$, $n_1 + n_2$-2, then the Null Hypothesis was rejected. Therefore there is enough evidence to support that end-to-end delay mean of Manual CE-to-CE and Automatic CE-to-CE tunneling mechanisms are less than 6to4 CE-to-CE and GRE CE-to-CE tunnel. Additionally, there is enough evidence to show that the 6to4 CE-to-CE tunnel has a lower mean delay than the GRE CE-to-CE tunnel.

4.1.2. Jitter

Jitter was also analyzed using similar techniques. The ANOVA results in Table 5 were obtained.

Table 5. ANOVA Results for Jitter of CE-to-CE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Auto CE	51864	82.52443	0.001591	4.14E-07
Manual CE	51753	82.6607	0.001597	4.05E-07
6to4 CE	51892	84.85763	0.001635	4.37E-07
GRE CE	51858	85.79141	0.001654	4.28E-07

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	0.000143	3	4.77E-05	113.4597	2.08E-73	2.604952
Within Groups	0.087257	207363	4.21E-07			
Total	0.0874	207366				

The Scheffe, F-Test, and T-Test are shown in Table 6 through Table 8.

Table 6. Scheffe Results for Jitter of CE-to-CE Tunnel

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
Auto CE vs. Manual CE	2.250164778	7.812	No
Auto CE vs. 6to4 CE	119.9061526	7.812	Yes
Auto CE vs. GRE CE	246.0015486	7.812	Yes
Manual CE vs. 6to4 CE	89.18991669	7.812	Yes
Manual CE vs. GRE CE	200.9596044	7.812	Yes
6to4 CE vs. GRE CE	22.43635151	7.812	Yes

Table 7. F-Test Results for Jitter of CE-to-CE Tunnel

F Distribution			
Transition Mechanism	F_{α}, n_1-1, n_2-1	F0	Test if $F_0 > F_{\alpha}$, n_1-1, n_2-1
Auto CE vs. 6to4 CE	1	0.945502653	No
Auto CE vs. GRE CE	1	0.967354954	No
Manual CE vs. 6to4 CE	1	0.924725465	No
Manual CE vs. GRE CE	1	0.946097566	No
6to4 CE vs. GRE CE	1	0.976769838	No

Table 8. T-Test Results for Jitter of CE-to-CE Tunnel

Two Sample T-Test			
Transition Mechanism	t_{α}, $n_1 + n_2$-2	t0	Test if $t_0 < -t_{\alpha}$, $n_1 + n_2$-2
Auto CE vs. 6to4 CE	1.64	-10.88907171	Yes
Auto CE vs. GRE CE	1.64	-15.68834028	Yes
Manual CE vs. 6to4 CE	1.64	-9.441690775	Yes
Manual CE vs. GRE CE	1.64	-14.25657544	Yes
6to4 CE vs. GRE CE	1.64	-4.672126496	Yes

The results show that there is enough evidence to support that end-to-end jitter means of Manual CE-to-CE and Automatic CE-to-CE are less than 6to4 CE-to-CE and GRE CE-to-CE tunnel, and 6to4 CE-to-CE has lower mean jitter than GRE CE-to-CE.

4.1.3. Throughput

Similar analysis was performed to evaluate throughput. The results of throughput show that there is not a significant difference among all of the 11 scenarios since F test < F critical. The ANOVA results for throughput are shown in Table 9.

Table 9. ANOVA Results for Throughput

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
6PE	54000	1.40604E+11	2603784	4.29E+12
IPv6	54000	1.40659E+11	2604795	4.28E+12
Dual Stack	54000	1.40624E+11	2604151	4.34E+12
Auto PE	54000	1.40654E+11	2604703	4.27E+12
GRE CE	54000	1.40721E+11	2605948	4.3E+12
GRE PE	54000	1.40671E+11	2605027	4.3E+12
Manual CE	54000	1.40645E+11	2604539	4.34E+12
Manual PE	54000	1.40654E+11	2604703	4.27E+12
6to4 CE	54000	1.40616E+11	2603998	4.31E+12
Auto CE	54000	1.4059E+11	2603527	4.32E+12

6to4 PE	54000	1.40671E+11	2605027	4.3E+12

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	2.49E +11	10	2.49E+ 10	0.0057 91	1	1.8307 2
Within Groups	2.55E +18	59398 9	4.3E+1 2			
Total	2.55E +18	59399 9				

4.2. Analysis of Objective 2

To determine if there is a statistically-significant difference among the performance metrics (delay, jitter, and throughput) of IPv6 ***PE-to-PE tunneling mechanisms*** and if so to determine which one is the superior method, the formulas below were used to accept or reject the hypothesis. Delay was analyzed using formulas similar to those used for Objective 1, and the results below were obtained.

4.2.1. Delay

The analysis of delay is described below.

ANOVA:

The hypothesis below was identified using ANOVA.

- Null Hypothesis (H0): Delay means are equal for PE-to-PE Tunneling mechanisms
- Alternative Hypothesis (H1): At least one delay mean for PE-to-PE Tunneling mechanism is different from other means

The results for delay performance metrics are shown in Table 10, where $F_{test} > F_{cv}$ therefore the Null Hypothesis is rejected and there is enough evidence to demonstrate that at least one delay mean is different from other delay means among the four scenarios.

Table 10. ANOVA Results for Delay of PE-to-PE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Manual PE	52022	107.5243	0.002066901	2.45E-06
Auto PE	52022	107.5243	0.002066901	2.45E-06
6to4 PE	51938	108.4085	0.002087268	2.39E-06
GRE PE	51938	108.4176	0.002087444	2.39E-06

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	2.17E -05	3	7.2494 2E-06	2.9912 61	0.0296 44	2.6049 52
Within Groups	0.503 891	20791 6	2.4235 3E-06			
Total	0.503 913	20791 9				

Scheffe's Method:

Scheffe's method demonstrates that there is a statistically-significant difference among delay means of the mechanisms where $F_S > F_C$, as shown in Table 11.

Table 11. Scheffe Results for Delay of PE-to-PE Tunnel

Scheffe's Method			
Transition Mechanisms	F_s	F_c	Test if $F_s > F_c$
Auto PE vs. Manual PE	0	7.812	No
Auto PE vs. 6to4 PE	8.448274198	7.812	Yes
Auto PE vs. GRE PE	8.525292432	7.812	Yes
Manual PE vs. 6to4 PE	8.448274198	7.812	Yes
Manual PE vs. GRE PE	8.525292432	7.812	Yes
6to4 PE vs. GRE PE	0.000330255	7.812	No

F-Test:

Next the F-Test was used to evaluate if variances are equal using the hypothesis below:

- Null Hypothesis (H0): delay variance i = delay variance j
- Alternative Hypothesis (H1): delay variance i < delay variance j

The results shown in Table 12 were obtained. Since $F_0 >$ F_{α} , n_1-1, n_2-1, then there is enough evidence to support that variances are not equal, therefore the T-Test with γ degree of freedom is used to find which delay mean is less.

Table 12. F-Test Results for Delay of PE-to-PE Tunnel

F Distribution			
Transition Mechanism	F_{α} , n_1 -1, n_2 -1	F0	Test if F_0 > F_{α} , n_1 -1, n_2 -1
Auto PE vs. 6to4 PE	1	1.024523462	Yes
Auto PE vs. GRE PE	1	1.024800865	Yes
Manual PE vs. 6to4 PE	1	1.024523462	Yes
Manual PE vs. GRE PE	1	1.024800865	Yes

T-Test using γ degree of freedom:

Next the T-Test with γ degree of freedom [13] was used using the hypothesis below:

- Null Hypothesis (H0): delay mean i = delay mean j
- Alternative Hypothesis (H1): delay mean i < delay mean j

The following formulas were used, with δ degrees of freedom:

$$t_0 = \frac{\bar{X}_i - \bar{X}_j}{\sqrt{\frac{S_i^2}{n_i} + \frac{S_j^2}{n_j}}} \qquad (10)$$

$$\delta = \frac{\left(\frac{S_i^2}{n_i} + \frac{S_j^2}{n_j}\right)^2}{\frac{\left(\frac{S_i^2}{n_i}\right)^2}{n_i - 1} + \frac{\left(\frac{S_j^2}{n_j}\right)^2}{n_j - 1}} \qquad (11)$$

The results are shown below in Table 13.

Table 13. T-Test Results for Delay of PE-to-PE Tunnel

T-Test Using γ degree of freedom			
Transition Mechanism	$t_{\alpha,\gamma}$	t0	Test if t0 < -t $_{\alpha,\gamma}$
Auto PE vs. 6to4 PE	1.64	-2.10904	Yes
Auto PE vs. GRE PE	1.64	-2.12737	Yes
Manual PE vs. 6to4 PE	1.64	-2.10904	Yes
Manual PE vs. GRE PE	1.64	-2.12737	Yes

Since t0 < -tc, then the Null Hypothesis was rejected. Therefore there is enough evidence to support that end-to-end delay means of Manual PE-to-PE and Automatic PE-to-PE tunneling mechanisms are less than the means for 6to4 PE-to-PE and GRE PE-to-PE tunnels.

4.2.2. *Jitter*

Jitter was also analyzed using the same techniques. The ANOVA results in Table 14 were obtained.

Table 14. ANOVA Results for Jitter of PE-to-PE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Manual PE	52021	83.55317109	0.001606143	4.47442E-07
Auto PE	52021	83.55317109	0.001606143	4.47442E-07
6to4 PE	51937	83.54239534	0.001608533	4.09939E-07
GRE PE	51937	83.59333751	0.001609514	4.09323E-07

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	4.5630 7E-07	3	1.5210 2E-07	0.3549 21286	0.7855 86345	2.6049 51992
Within Groups	0.0891 01094	2079 12	4.2855 2E-07			
Total	0.0891 01551	2079 15				

Since the F test < F critical, the Null Hypothesis was accepted. Therefore there is enough evidence to show that there is no statistically-significant difference among the jitter means of PE-to-PE tunneling mechanisms.

4.3. *Analysis of Objective 3*

To determine if there is a statistically-significant difference among the performance metrics (delay, jitter, throughput) of *IPv6* ***PE-to-PE and IPv6 CE-to-CE tunneling mechanisms*** and if so to determine which one is the superior method, the formulas below were used.

To analyze Objective 3, we first determined if there are statistically-significant differences among the performance metrics (delay, jitter, throughput) of Manual/Automatic PE-to-PE and Manual/Automatic CE-to-CE tunneling mechanisms and if so which one is the superior method. Next we compared the GRE PE-to-PE and GRE CE-to-CE. Finally, we compared the 6to4 PE-to-PE and 6to4 CE-to-CE tunneling mechanisms. Delay was analyzed first, followed by jitter and throughput using formulas similar to those used in Objective 1. The following results were obtained.

4.3.1. *Delay*

The analysis of delay is shown in ANOVA, Scheffe, F-Test, and T-Test below, in Table 15 through Table 18.

Table 15. ANOVA Results for Delay of Auto/Manual PE-to-PE and CE-to-CE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Auto PE	52022	107.5243487	0.002066901	2.45303E-06
Auto CE	51865	108.5075339	0.002092115	2.44078E-06

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	1.6510 5E-05	1	1.6510 5E-05	6.7474 74406	0.0093 89372	3.8415 48336
Within Groups	0.2541 9782	10 38 85	2.4469 2E-06			
Total	0.2542 14331	10 38 86				

Table 16. Scheffe Results for Delay of Auto/Manual PE-to-PE and CE-to-CE Tunnel

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
Auto PE vs. Auto CE	6.747474357	3.84	Yes

Table 17. F-Test Results for Delay of Auto/Manual PE-to-PE and CE-to-CE Tunnel

F Distribution			
Transition Mechanism	F_{α, n_1-1, n_2-1}	F0	Test if $F_0 > F_{\alpha, n_1-1, n_2-1}$
Auto PE vs. Auto CE	1	1.005017486	Yes

Table 18. T-Test Results for Delay of Auto/Manual PE-to-PE and CE-to-CE Tunnel

T-Test Using γ degree of freedom			
Transition Mechanism	$t_{\alpha,\gamma}$	t0	Test if t0 < -t $_{\alpha,\gamma}$
Auto PE vs. Auto CE	1.644868295	-2.59759993	Yes

The results show that there is enough evidence to support that the end-to-end delay mean of Automatic/Manual PE-to-PE is less than the delay mean of Automatic/Manual CE-to-CE tunneling mechanism.

Similar analysis was performed for delay mean of GRE PE-to-PE compared to GRE CE-to-CE, and for 6to4 PE-to-PE compared to 6to4 CE-to-CE. The results show that there is enough evidence to support that end-to-end delay mean of GRE PE-to-PE is less than GRE CE-to-CE tunnel, and that end-to-end delay mean of 6to4 PE-to-PE is less than 6to4 CE-to-CE tunnel.

Similar analysis was performed for delay mean of GRE PE-to-PE compared to Automatic CE-to-CE tunnel. The results show that there is enough evidence to support that end-to-end delay mean of GRE PE-to-PE is less than Automatic CE-to-CE tunnel.

4.3.2. Jitter

Jitter was also analyzed using the same techniques. The ANOVA, Scheffe, F-Test, and T-Test results in Table 19 through Table 22 were obtained for Automatic/Manual CE-to-CE and PE-to-PE tunnels.

Table 19. ANOVA Results for Jitter of Automatic/Manual PE-to-PE and CE-to-CE Tunnel

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Auto CE	51864	82.52443	0.001591	4.14E-07
Auto PE	52021	83.55317	0.001606	4.47E-07

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	5.82E -06	1	5.82E -06	13.523 89	0.0002 36	3.8415 48
Within Groups	0.044 727	103883	4.31E -07			
Total	0.044 733	103884				

Table 20. Scheffe Results for Jitter of Automatic/Manual PE-to-PE and CE-to-CE Tunnel

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
Auto CE vs. Auto PE	13.52388595	3.84	Yes

Table 21. F-Test Results for Jitter of Automatic/Manual PE-to-PE and CE-to-CE Tunnel

F Distribution			
Transition Mechanism	F_{α, n_1-1, n_2-1}	F0	Test if $F_0 > F_{\alpha, n_1-1, n_2-1}$
Auto CE vs. Auto PE	1	1.081812147	Yes

Table 22. T-Test Results for Jitter of Automatic/Manual PE-to-PE and CE-to-CE Tunnel

T-Test Using γ degree of freedom			
Transition Mechanism	$t_{\alpha,\gamma}$	t0	Test if $t0 < -t_{\alpha,\gamma}$
Auto CE vs. Auto PE	1.644868295	-3.677702063	Yes

The results show there is enough evidence to support that end-to-end jitter mean of Automatic CE-to-CE is less than Automatic PE-to-PE tunnel. The same is true for Manual tunnel, where end-to-end delay mean of Manual CE-to-CE is less than Manual PE-to-PE tunnel since there is no statistically-significant difference between Manual and Automatic tunnels for both scenarios.

Jitter was also analyzed using the same techniques for comparing GRE CE-to-CE and GRE PE-to-PE tunnels and for comparing 6to4 CE-to-CE and 6to4 PE-to-PE. The results show that there is enough evidence to support that end-to-end jitter mean of GRE PE-to-PE is less than GRE CE-to-CE tunnel. Similarly, the results show that the end-to-end jitter mean of 6to4 PE-to-PE is less than 6to4 CE-to-CE tunnel.

Similar analysis was performed for jitter mean of GRE PE-to-PE compared to 6to4 CE-to-CE tunnel. The results show that there is enough evidence to support that end-to-end jitter mean of GRE PE-to-PE is less than 6to4 CE-to-CE tunnel.

4.4. Analysis of Objective 4

To determine if there are statistically-significant differences among the performance metrics (delay, jitter, and throughput) of **6PE, Dual Stack, Native IPv6, and best tunneling mechanism**, and if so to determine which one is the superior method, the formulas below were used to accept or reject the hypothesis. Delay was analyzed first, followed by jitter and throughput using formulas similar to those used in Objective 1. The following results were obtained.

4.4.1. Delay

The analysis of delay is shown in Table 23 through Table 26.

Table 23. ANOVA Results for Delay of 6PE, Dual Stack, and IPv6

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
6PE	51940	102.8062842	0.001979328	2.28725E-06
Dual Stack	51768	103.3998435	0.00199737	2.27278E-06
IPv6	52124	106.34409	0.002040214	2.38408E-06

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	0.00010 1805	2	5.09 027 E-05	21.989 80503	2.83E -10	2.99579
Within Groups	0.36071 8136	15582 9	2.31 483 E-06			
Total	0.36081 9941	15583 1				

Table 24. Scheffe Results for Delay of 6PE, Dual Stack, and IPv6

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
6PE vs. Dual Stack	3.645908778	5.99158	No
6PE vs. IPv6	41.66304039	5.99158	Yes
Dual Stack vs. IPv6	20.59540711	5.99158	Yes

Table 25. F-Test Results for Delay of 6PE, Dual Stack, and IPv6

F Distribution			
Transition Mechanism	F_{α, n_1-1, n_2-1}	F0	Test if $F_0 > F_{\alpha, n_1-1, n_2-1}$
6PE vs. IPv6	1	0.959384957	No
Dual Stack vs. IPv6	1	0.953317311	No

Table 26. T-Test Results for Delay of 6PE, Dual Stack, and IPv6

T-Test (Two Sample)			
Transition Mechanism	$t_{\alpha, n_1 + n_2 - 2}$	t0	Test if $t0 < -t_{\alpha, n_1 + n_2 - 2}$
6PE vs. IPv6	1.644	-6.425847667	Yes
Dual Stack vs. IPv6	1.644	-4.524846091	Yes

The results show that there is enough evidence to support that the end-to-end delay mean of Dual Stack and 6PE is less than Native IPv6.

Similar analysis was performed for delay mean of Native IPv6 compared to Automatic PE-to-PE tunnel. The results show that there is enough evidence to support that end-to-end delay mean of Native IPv6 is less than Automatic PE-to-PE tunnel.

4.4.2. Jitter

Jitter was also analyzed using the same techniques. The ANOVA, Scheffe, F-Test, and T-Test results are shown in Table 27 through Table 30.

Table 27. ANOVA Results for Jitter of 6PE, Dual Stack, and IPv6

ANOVA: Single Factor				
Groups	Count	Sum	Average	Variance
Dual Stack	51768	79.32556571	0.001532328	3.90404E-07
6PE	51940	80.14309779	0.001542994	1.61809E-07
IPv6	52124	82.21228876	0.001577244	4.33525E-07

Source of Variation	SS	df	MS	F	P-Value	F crit
Between Groups	5.72776E-05	2	2.86388E-05	87.14488564	0	2.995789866
Within Groups	0.051210797	155829	3.28635E-07			
Total	0.051268075	155831				

Table 28. Scheffe Results for Jitter of 6PE, Dual Stack, and IPv6

Scheffe's Method			
Transition Mechanisms	Fs	Fc	Test if Fs > Fc
6PE vs. Dual Stack	8.974473545	5.99579	Yes
6PE vs. IPv6	159.4448874	5.99579	Yes
Dual Stack vs. IPv6	92.86737671	5.99579	Yes

Table 29. F Distribution Results for Jitter of 6PE, Dual Stack, and IPv6

F Distribution			
Transition Mechanism	$F_{\alpha, n_1 - 1, n_2 - 1}$	F0	Test if $F_0 > F_{\alpha, n_1 - 1, n_2 - 1}$
6PE vs. Dual Stack	1	0.414464672	No
Dual Stack vs. IPv6	1	0.900534006	No
6PE vs. IPv6	1	0.373239532	No

Table 30. T-Test Results for Jitter of 6PE, Dual Stack, and IPv6

T-Test (Two Sample)			
Transition Mechanism	$t_{\alpha, n_1 + n_2 - 2}$	t0	Test if $t0 < -t_{\alpha, n_1 + n_2 - 2}$
Dual Stack vs. 6PE	1.644	-3.269431816	Yes
6PE vs. IPv6	1.644	-10.12157359	Yes
Dual Stack vs. IPv6	1.644	-11.27699282	Yes

The analysis shows there is enough evidence to support that end-to-end jitter mean of Dual Stack is less than 6PE. Also, the end-to-end jitter mean of Dual Stack is less than IPv6. Additionally, the end-to-end jitter mean of 6PE is less than Native IPv6.

Similar analysis was performed for jitter mean of Native IPv6 compared to Automatic CE-to-CE tunnel. The results show there is enough evidence to support that end-to-end jitter mean of Native IPv6 is less than Automatic CE-to-CE tunnel.

5. Results

The statistical analysis for delay, jitter, and throughput was performed to identify if there is a statistically-significant difference among these scenarios and if so to determine which one(s) are the superior methods, in the order of best to worst. The detailed analysis is described in the Analysis section above. This section summarizes the results obtained from previous sections.

The results for delay including the ordinal ranking values are shown in Table 31, with 6PE and Dual Stack having the lowest delay and GRE CE-to-CE having the highest delay.

Table 31. Lowest to Highest Delay IPv6 Transition Mechanism

IPv6 Transition Mechanisms in Order of Lowest to Highest Delay	Ordinal Ranking Value
6PE and Dual Stack	1
Native IPv6	3
Manual PE-to-PE and Automatic PE-to-PE	4
6to4 PE-to-PE and GRE PE-to-PE	6
Manual CE-to-CE and Automatic CE-to-CE	8
6to4 CE-to-CE	10
GRE CE-to-CE	11

The results for jitter including the ordinal ranking values are shown in Table 32, with Dual Stack having the lowest jitter and GRE CE-to-CE having the highest jitter.

Table 32. Lowest to Highest Jitter IPv6 Transition Mechanism

IPv6 Transition Mechanisms in Order of Lowest to Highest Jitter	Ordinal Ranking Value
Dual Stack	1
6PE	2
Native IPv6	3
Manual CE-to-CE and Automatic CE-to-CE	4
Manual PE-to-PE, Automatic PE-to-PE, 6to4 PE-to-PE, and GRE PE-to-PE	6
6to4 CE-to-CE	10
GRE CE-to-CE	11

For throughput, the analysis shows that there is no statistically-significant difference among these 11 mechanisms.

Next the main objective of this research is analyzed, which is to rank the aforementioned IPv6 transition mechanisms from best to worst. The best mechanism offers lowest delay, lowest jitter, and highest throughput. The ordinal value analysis was performed to rank the delay, jitter, and throughput to analyze the **overall performance metrics ranking of the aforementioned transition mechanisms** described as Objective 5. The transition mechanisms were ranked using Table 31 and Table 32. The overall IPv6 transition mechanism performance metrics rankings are shown in Table 33, in order of best to worst considering lowest delay, lowest jitter, and highest throughput. The ordinal ranking value and the overall ranking are shown in this table.

Table 33. Best to Worst Overall IPv6 Transition Mechanism

Overall (including delay, jitter, and throughput) IPv6 Transition Mechanisms in Order of Best to Worst	Ordinal Ranking Value	Overall Ranking
Dual Stack	3	1
6PE	4	2
Native IPv6	7	3
Manual PE-to-PE and Automatic PE-to-PE	11	4
Manual CE-to-CE, Automatic CE-to-CE, 6to4 PE-to-PE, and GRE PE-to-PE	13	6
6to4 CE-to-CE	21	10
GRE CE-to-CE	23	11

The results show that the Dual Stack has the best overall performance metrics with the lowest delay, lowest jitter, and highest throughput. The GRE CE-to-CE has the worst overall performance metrics.

6. Conclusion and Future Work

This research analyzed a series of IPv6 transition mechanisms over MPLS backbone using OPNET as a simulation tool. We performed statistical analysis and evaluated IPv6 transition mechanisms' performance metrics of end-to-end delay, jitter, and throughput. Using statistical models, we ranked the IPv6 transition mechanisms and identified the superior mechanisms that offer the lowest delay, lowest jitter, and highest throughput.

The results show that the Dual Stack has the best overall performance metrics with the lowest delay, lowest jitter, and highest throughput, followed by 6PE; Native IPv6; Manual PE-to-PE and Automatic PE-to-PE; Manual CE-to-CE, Automatic CE-to-CE, 6to4 PE-to-PE, and GRE PE-to-PE; 6to4 CE-to-CE; and GRE CE-to-CE, as shown in Table 33.

The results obtained from this analysis will be critical for those who want to implement IPv6 and are concerned about the performance of the transition mechanisms. Given the acquisition cost, schedule, risk, and technical challenges in supporting IPv6, this analysis will increase confidence about making informed decisions and choosing the appropriate IPv6 transition mechanism depending on the desired performance.

The future work should focus on adding other transition mechanisms to the analysis, such as ISATAP, Teredo, and 6VPE. Currently, OPNET does not support these transition mechanisms. Unless another modeling and simulation tool is used, one has to wait until these mechanisms are included in the OPNET tool. The analysis of a comprehensive set of IPv6 transition mechanisms is critical and advantageous to the technical community.

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