

The Resilience of Different Topologies to Link Connection Failure

Using Dijkstra's Algorithm on different network topologies to determine which is most resistant to a link failure.

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Abstract— The goal of this experiment was to find the shortest path of one node to five other individual nodes. There are three different topologies being used: mesh, ring, and fully connected. The shortest path was discovered, but timing how long each path took and then installing routing rules to specify to take that path. In each topology, three separate trials were connected where we took down certain routes to see how it affects the shortest route path.

Keywords—*component; formatting; style; styling; insert (key words)*

I. INTRODUCTION

The goal of this experiment is to see which network topologies are the most resistant to a link failure, more specifically, link failures near the transmitting node. Data packets are sent to each node from adjacent nodes to find each link's cost, and Dijkstra's algorithm is used to find the shortest paths to each node. Three trials are

conducted for each topology. In the first trial, the shortest paths with all original links intact are found. In the second trial, the least costly link goes down, {goes to infinity}, from the transmitting node, and the shortest paths are found. The third trial is the same as the second trial, but the second least costly link goes down instead of the least costly link from the transmitting node.

Three network topologies are tested: mesh, ring, and fully-connected. Each topology used six nodes. The mesh topology has a minimum of one link connection and three link connections for each node, where they are seemingly randomly connected. The ring topology had a ring of six nodes connected in a circle, so each node had two links. The fully-connected topology had six nodes all connected to each other, so each node had five links.

Fraida Fund's *Dijkstra's shortest path algorithm* experiment was used as a reference for the experiment, where we used her one-site experiment (that required the reservation of only one resource on GENI for each topology), where we would send data packets to nodes by pinging them, which would give us the cost of each node, as well as making new routing rules and getting routing tables [1].

II. EMULATION DESCRIPTION

A. Setup

The GENI tutorial we used as a basis for our project provided a URL to configure our resources [1]. Upon importing the URL, our resources were configured in the mesh topology

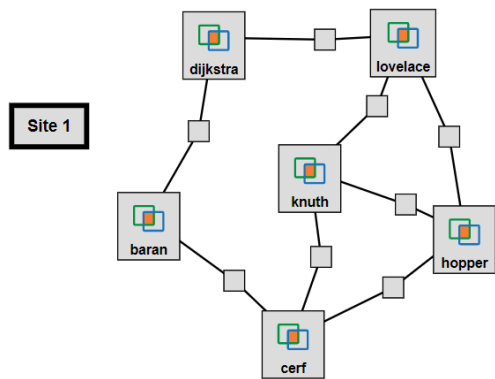


Figure 1: Mesh Topology in GENI

For subsequent topologies we loaded the URL before adding/removing links as needed.

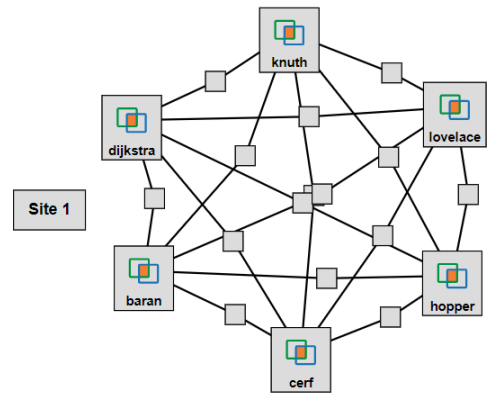


Figure 2: Fully-Connected Topology in GENI

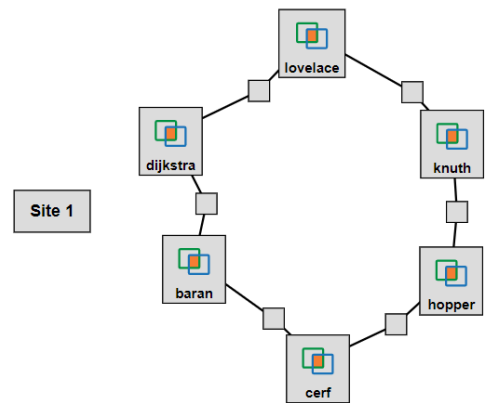


Figure 3: Ring Topology in GENI

Each node also was configured to display the status of each of its node links, as well as having the “mtr” function pre-installed. These tools were extremely valuable during the emulation process.

```
-----
Link on eth1 (10.10.4.2 to 10.10.4.1) is up
Link on eth2 (10.10.5.1 to 10.10.5.2) is up
-----
vnatiell@dijkstra:~$
```

Figure 4: Example Link Status Display

B. Emulation Process

The emulation itself consisted of using different ping and routing instructions to perform

Dijkstra's Algorithm. We first ran the "ping" command from each node to each of its links to determine the 'cost' (in milliseconds) of transmitting a packet of data.

```
vnnatiell@dijkstra:~$ ping -c 25 10.10.4.1
```

Figure 5: Example of "ping" Command

Once each link cost was determined, we created a topography chart, listing each node and its respective network addresses as well as the cost between each link.

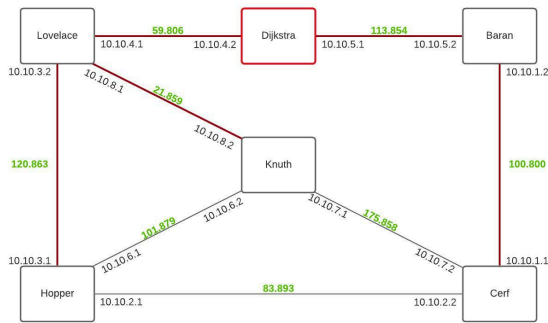


Figure 6: Mesh Topography Chart

From here, we performed Dijkstra's Algorithm to find the cheapest path from the "dijkstra" node to all five remaining nodes on the network. A table was used to keep track of calculated node costs and for displaying the calculated cost to each node. As per Dijkstra's Algorithm, once we chose the shortest pathway available, that pathway was locked down and more nodes became available. This process was repeated until a pathway was found to each node from the "dijkstra" node.

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	0	∞	∞	∞	∞	∞
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	∞	∞	113.854	∞
2	cerf, lovelace, hopper, knuth	dijkstra, baran	baran	-	0	214.654	∞	∞	113.854
3	lovelace, hopper, knuth	dijkstra, baran, cerf	cerf	-	0	214.654	∞	298.547	390.512
4	lovelace, knuth	dijkstra, baran, cerf, hopper	hopper	-	0	214.654	419.41	298.547	390.512
5	lovelace	dijkstra, baran, cerf, hopper, knuth	knuth	-	0	214.654	412.371	298.547	390.512
6	-	dijkstra, baran, cerf, hopper, knuth, lovelace	lovelace	-	0	214.654	412.371	298.547	390.512

Table 1: Example of Dijkstra Table

Upon calculating our predicted shortest path costs, we moved on to adding the proper routes to each node. We utilized the "route add" command to manually add the proper routes to each node's routing table.

```
sudo route add -net 10.10.2.0/24 gw 10.10.4.1
```

Figure 7: Example of "route add" Command

```
vnnatiell@dijkstra:~$ route -n
```

Destination	Gateway	Genmask	Flags	Metric	Ref	Use	Iface
0.0.0.0	172.16.0.1	0.0.0.0	UG	1024	0	0	eth0
10.10.2.0	10.10.4.1	255.255.255.0	UG	0	0	0	eth1
10.10.4.0	0.0.0.0	255.255.255.0	U	0	0	0	eth1
10.10.5.0	0.0.0.0	255.255.255.0	U	0	0	0	eth2
10.10.6.0	10.10.4.1	255.255.255.0	UG	0	0	0	eth1
10.10.8.0	10.10.4.1	255.255.255.0	UG	0	0	0	eth1
172.16.0.0	0.0.0.0	255.240.0.0	U	0	0	0	eth0
172.16.0.1	0.0.0.0	255.255.255.255	UH	1024	0	0	eth0

Figure 8: Routing Table after Completion of Routing

Finally, all that remained was to verify our predictions by sending packets to each node and measuring how long they took to reach their destinations. For this, we used the "mtr" command.

```
marlalop@dijkstra:~$ mtr 10.10.7.1 --report --no-dns
```

Start:	2021-08-04T21:41:57-0700						
HOST:	dijkstra.project.ch-geni-ne						
	Loss%	Snt	Last	Avg	Best	Wrst	StDev
1.1-- 10.10.5.2	0.0%	10	113.8	113.8	113.6	113.9	0.1
2.1-- 10.10.1.1	0.0%	10	214.5	214.6	214.4	214.7	0.1
3.1-- 10.10.7.1	0.0%	10	390.3	390.3	390.1	390.5	0.1

Figure 9: Example of "mtr" Command

After verifying our predictions for each route cost, the trial was complete. For each subsequent

trial, one link was taken down to simulate a real-world loss in connection between nodes. From there, we repeated the process, for a total of three trials per topography, or a total of nine trials.

C. Results

The first topology tested was the mesh topology. The upon completing the algorithm with all links up, the shortest pathways were calculated as such (with the shortest routes highlighted in red):

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	-	0	∞	∞	∞	∞
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	59.806	∞	113.854	∞
2	cerf, hopper, baran, knuth	dijkstra, lovelace	lovelace	-	0	59.806	180.669	113.854	81.665
3	cerf, hopper, baran	dijkstra, lovelace, knuth	knuth	-	0	257.523	59.806	180.669	113.854
4	cerf, hopper	dijkstra, lovelace, knuth, baran	baran	-	0	214.654	59.806	180.669	113.854
5	cerf	dijkstra, lovelace, knuth, baran, hopper	hopper	-	0	214.654	59.806	180.669	113.854
6	-	dijkstra, lovelace, knuth, baran, hopper, cerf	cerf	-	0	214.654	59.806	180.669	113.854

Table 2: Trial 1 Result of Mesh Topology

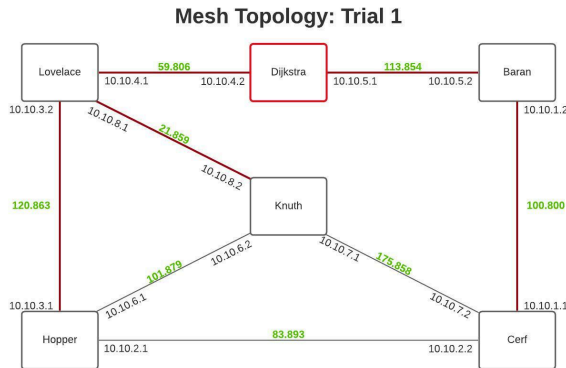


Figure 10: Trial 1 Result of Mesh Topology

After running the “mtr” command for each node, we verified that our calculated costs were correct:

```

marialop@dijkstra:~$ mtr 10.10.1.1 --report --no-dns
Start: 2021-08-04T20:05:02-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 114.0 113.9 113.8 114.1 0.1
 2.|-- 10.10.1.1 0.0% 10 214.7 214.7 214.6 214.9 0.1

marialop@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-08-04T20:00:35-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 59.8 59.8 59.6 60.0 0.1
 2.|-- 10.10.3.1 0.0% 10 180.6 180.7 180.6 180.8 0.1

marialop@dijkstra:~$ mtr 10.10.3.1 --report --no-dns
Start: 2021-08-04T20:03:14-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 59.8 59.9 59.7 60.2 0.1
 2.|-- 10.10.3.1 0.0% 10 180.6 180.7 180.6 180.8 0.1

marialop@dijkstra:~$ mtr 10.10.5.2 --report --no-dns
Start: 2021-08-04T19:58:02-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 113.9 113.9 113.9 114.0 0.1
 2.|-- 10.10.5.2 0.0% 10 113.9 113.9 113.9 114.0 0.1

marialop@dijkstra:~$ mtr 10.10.8.2 --report --no-dns
Start: 2021-08-04T20:01:47-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 59.8 59.9 59.8 60.1 0.1
 2.|-- 10.10.8.2 0.0% 10 81.6 81.6 81.5 81.8 0.1

```

Figure 11: Trial 1 mtr results in order of: cerf, lovelace, hopper, baran, knuth

With all nodes connected, the average cost to transmit to any other node was 130.13 ms. This was achieved with the use of 8 links between nodes. The results for trials 2 and 3 are as follows:

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	-	0	∞	∞	∞	∞
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	∞	∞	113.854	∞
2	cerf, lovelace, hopper, knuth	dijkstra, baran	baran	-	0	214.654	∞	113.854	∞
3	lovelace, hopper, knuth	dijkstra, baran, cerf	cerf	-	0	214.654	298.547	113.854	390.512
4	lovelace, knuth	dijkstra, baran, cerf, hopper	hopper	-	0	214.654	419.41	298.547	113.854
5	lovelace	dijkstra, baran, cerf, hopper, knuth	knuth	-	0	214.654	412.371	298.547	113.854
6	-	dijkstra, baran, cerf, hopper, knuth, lovelace	lovelace	-	0	214.654	412.371	298.547	113.854

Table 3: Trial 2 Result of Mesh Topology

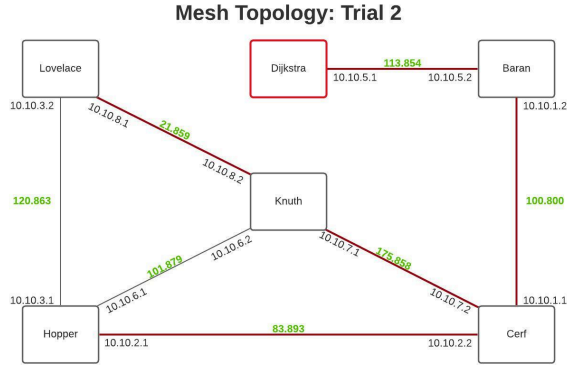


Figure 12: Trial 2 Result of Mesh Topology

```
marialop@dijkstra:~$ mtr 10.10.1.1 --report --no-dns
Start: 2021-08-04T21:42:48-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.5.2 0.0% 10 113.9 113.8 113.7 114.0 0.1
 2|-- 10.10.1.1 0.0% 10 214.6 214.6 214.5 214.6 0.0

marialop@dijkstra:~$ mtr 10.10.8.1 --report --no-dns
Start: 2021-08-04T21:38:51-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.5.2 0.0% 10 113.8 113.8 113.8 114.0 0.1
 2|-- 10.10.1.1 0.0% 10 214.4 214.5 214.3 214.8 0.1
 3|-- 10.10.7.1 0.0% 10 390.1 407.9 390.1 566.3 55.7
 4|-- 10.10.8.1 0.0% 10 412.1 419.6 411.9 487.9 24.0

marialop@dijkstra:~$ mtr 10.10.2.1 --report --no-dns
Start: 2021-08-04T21:40:25-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.5.2 0.0% 10 113.9 113.9 113.9 114.0 0.0
 2|-- 10.10.1.1 0.0% 10 214.6 214.6 214.3 214.7 0.1
 3|-- 10.10.2.1 0.0% 10 298.4 306.7 298.3 382.0 26.5

marialop@dijkstra:~$ mtr 10.10.5.2 --report --no-dns
Start: 2021-08-04T21:43:42-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.5.2 0.0% 10 113.9 113.9 113.8 114.0 0.1

marialop@dijkstra:~$ mtr 10.10.7.1 --report --no-dns
Start: 2021-08-04T21:41:57-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.5.2 0.0% 10 113.8 113.8 113.6 113.9 0.1
 2|-- 10.10.1.1 0.0% 10 214.5 214.6 214.4 214.7 0.1
 3|-- 10.10.7.1 0.0% 10 390.3 390.3 390.1 390.5 0.1
```

Figure 13: Trial 2 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 2 found an average transmission cost of 285.99 ms, with the use of 7 links.

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	-	0	-	-	-	-
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	59.806	-	-	-
2	cerf, hopper, baran, knuth	dijkstra, lovelace	lovelace	-	0	59.806	180.669	-	81.665
3	cerf, hopper, baran	dijkstra, lovelace, knuth	knuth	0	257.523	59.806	180.669	-	81.665
4	cerf, baran	dijkstra, lovelace, knuth, hopper	hopper	0	257.523	59.806	180.669	-	81.665
5	baran	dijkstra, lovelace, knuth, hopper, cerf	cerf	0	257.523	59.806	180.669	358.323	81.665
6	-	dijkstra, lovelace, knuth, hopper, cerf, baran	baran	0	257.523	59.806	180.669	358.323	81.665

Table 4: Trial 3 Result of Mesh Topography

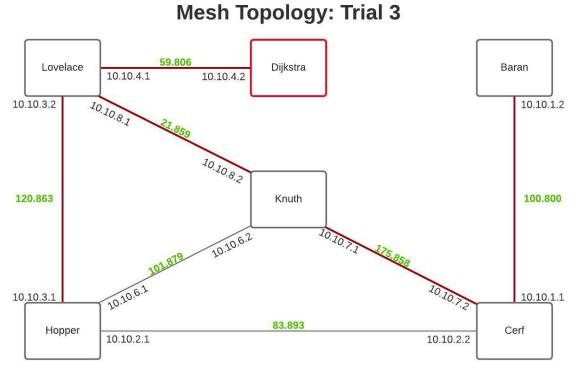


Figure 14: Trial 3 Result of Mesh Topography

```
marialop@dijkstra:~$ mtr 10.10.7.2 --report --no-dns
Start: 2021-08-04T22:39:24-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.4.1 0.0% 10 59.8 59.8 59.6 60.0 0.1
 2|-- 10.10.8.2 0.0% 10 81.5 81.6 81.5 81.8 0.1
 3|-- 10.10.7.2 0.0% 10 257.4 257.3 257.0 257.4 0.1

marialop@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-08-04T22:36:43-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.4.1 0.0% 10 60.0 59.9 59.7 60.0 0.1

marialop@dijkstra:~$ mtr 10.10.3.1 --report --no-dns
Start: 2021-08-04T22:37:48-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.4.1 0.0% 10 59.8 59.9 59.8 60.1 0.1
 2|-- 10.10.3.1 0.0% 10 180.9 180.6 180.3 180.9 0.2

marialop@dijkstra:~$ mtr 10.10.1.2 --report --no-dns
Start: 2021-08-04T22:40:18-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.4.1 0.0% 10 59.8 59.9 59.6 60.0 0.1
 2|-- 10.10.8.2 0.0% 10 81.7 81.7 81.5 81.8 0.1
 3|-- 10.10.7.2 0.0% 10 257.4 257.4 257.2 257.5 0.1
 4|-- 10.10.1.2 0.0% 10 358.1 358.0 357.7 358.3 0.2

marialop@dijkstra:~$ mtr 10.10.8.2 --report --no-dns
Start: 2021-08-04T22:38:37-0700
HOST: dijkstra.project.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
 1|-- 10.10.4.1 0.0% 10 59.8 59.8 59.6 59.9 0.1
 2|-- 10.10.8.2 0.0% 10 81.5 81.6 81.5 81.6 0.0
```

Figure 15: Trial 3 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 3 found an average transmission cost of 187.60 ms, with the use of 7 links. By removing a link from this topography, the average increase in transmission cost was 106.67 ms, or 15.24 ms per link.

The second topology used was the Ring topology. The results of each trial were as follows:

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	dijkstra	-	0	-	-	-	-	-
1	cerf, lovelace, hopper, baran, knuth	dijkstra	baran, lovelace	-	0	133.9	-	76.9	-
2	cerf, hopper, knuth	dijkstra, baran	lovelace, cerf	-	0	208.5	133.9	76.9	-
3	hopper	dijkstra, baran, lovelace, cerf, knuth	-	0	208.5	133.9	-	76.9	164.6
4		dijkstra, baran, lovelace, cerf, hopper	-	0	208.5	133.9	352.4	76.9	164.6
5		dijkstra, baran, lovelace, hopper	-	0	208.5	133.9	262.2	76.9	164.6
6			-	0	208.5	133.9	262.2	76.9	164.6

Table 5: Trial 1 Result of Ring Topography

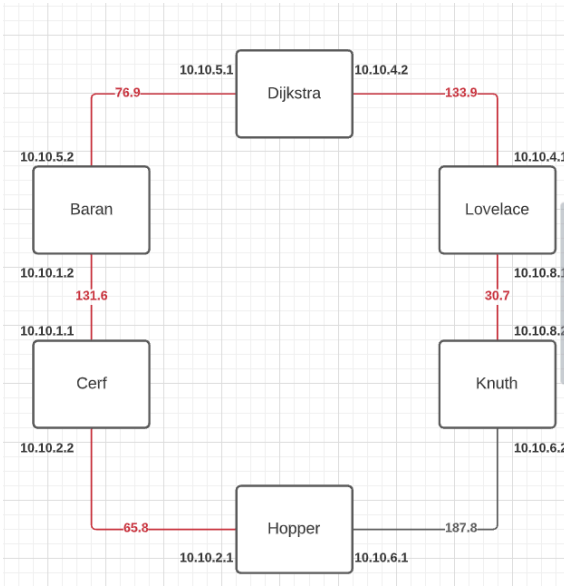


Figure 16: Trial 1 Result of Ring Topography

```

vnatiell@dijkstra:~$ mtr 10.10.1.1 --report --no-dns
Start: 2021-08-05T14:12:06-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.9 76.9 76.8 77.0 0.0
 2.|-- 10.10.1.1 0.0% 10 196.5 208.5 196.5 316.1 37.8

vnatiell@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-08-05T14:09:58-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.9 133.9 133.8 134.1 0.1

vnatiell@dijkstra:~$ mtr 10.10.2.1 --report --no-dns
Start: 2021-08-05T14:13:07-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.8 76.8 76.8 76.9 0.0
 2.|-- 10.10.1.1 0.0% 10 196.4 196.4 196.3 196.4 0.0
 3.|-- 10.10.2.1 0.0% 10 262.2 262.2 262.1 262.2 0.0

vnatiell@dijkstra:~$ mtr 10.10.5.2 --report --no-dns
Start: 2021-08-05T14:11:25-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 77.0 77.0 76.9 77.1 0.0

vnatiell@dijkstra:~$ mtr 10.10.8.2 --report --no-dns
Start: 2021-08-05T14:10:45-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.9 133.9 133.8 133.9 0.0
 2.|-- 10.10.8.2 0.0% 10 164.7 164.7 164.7 164.8 0.0

```

Figure 17: Trial 1 mtr results in order of: cerf, lovelace, hopper, baran, knuth

With all nodes connected, the average cost to transmit to any other node was 169.22 ms. This was achieved with the use of 6 links between nodes. The results for trials 2 and 3 are as follows:

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	-	-	-	-
1	cerf, lovelace, hopper, baran, knuth	dijkstra	baran, lovelace	-	0	133.9	-	76.9	-
2	cerf, hopper, knuth	dijkstra, baran	lovelace, cerf	-	0	196.5	133.9	76.9	-
3	hopper, knuth	dijkstra, baran, lovelace, cerf	-	0	196.5	133.9	-	76.9	-
4	knuth	dijkstra, baran, lovelace, hopper	-	0	196.5	133.9	262	76.9	-
5		dijkstra, baran, lovelace, knuth	-	0	196.5	133.9	262	76.9	450.1
6			-	0	196.5	133.9	262	76.9	450.1

Table 6: Trial 2 Result of Ring Topography

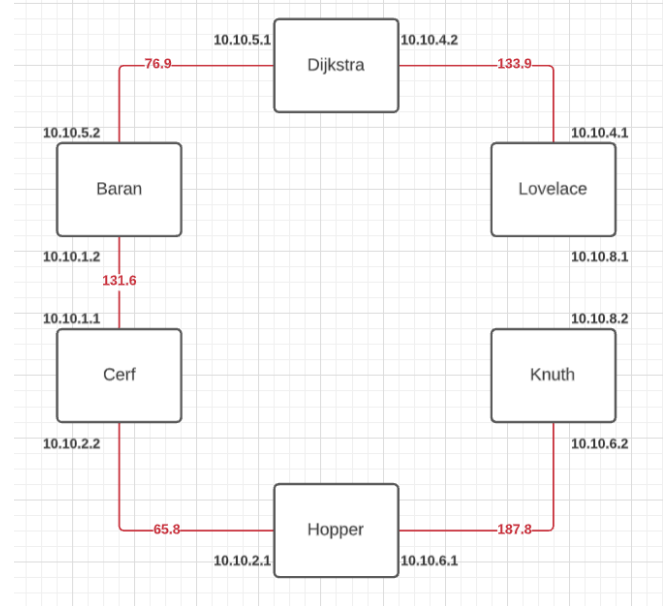


Figure 18: Trial 2 Result of Ring Topography

```

vnatiell@dijkstra:~$ mtr 10.10.1.1 --report --no-dns
Start: 2021-08-05T13:23:55-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.9 76.9 76.9 77.0 0.0
 2.|-- 10.10.1.1 0.0% 10 196.4 196.4 196.4 196.4 0.0

vnatiell@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-08-05T13:24:45-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.8 133.9 133.8 134.0 0.1

vnatiell@dijkstra:~$ mtr 10.10.2.1 --report --no-dns
Start: 2021-08-05T13:23:31-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.9 76.9 76.9 77.1 0.1
 2.|-- 10.10.1.1 0.0% 10 196.4 196.4 196.4 196.5 0.0
 3.|-- 10.10.2.1 0.0% 10 262.1 262.1 262.1 262.2 0.0

```

```
vnnatiell@dijkstra:~$ mtr 10.10.5.2 --report --no-dns
Start: 2021-08-05T13:24:19-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.8 76.9 76.8 77.0 0.1
```

```
vnnatiell@dijkstra:~$ mtr 10.10.6.2 --report --no-dns
Start: 2021-08-05T13:22:14-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 77.0 77.0 76.9 77.1 0.1
 2.|-- 10.10.1.1 0.0% 10 196.5 196.5 196.4 196.5 0.0
 3.|-- 10.10.2.1 0.0% 10 262.2 262.2 262.1 262.2 0.0
 4.|-- 10.10.6.2 0.0% 10 450.0 450.0 449.9 450.1 0.0
```

Figure 19: Trial 2 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 2 found an average transmission cost of 223.86 ms, with the use of 5 links.

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	-	-	-	-	-
1	cerf, lovelace, hopper, baran, knuth	dijkstra	baran, lovelace	-	133.9	-	-	76.9	-
2	knuth, hopper, cerf	dijkstra, lovelace	lovelace, knuth	-	133.9	76.9	-	-	164.6
3	hopper, cerf	dijkstra, baran, lovelace, knuth	knuth	-	133.9	76.9	-	-	164.6
4	cerf	dijkstra, baran, lovelace, hopper	hopper	-	133.9	352.4	76.9	-	164.6
5		dijkstra, baran, lovelace, cerf	cerf	-	418.2	133.9	352.4	76.9	164.6
6				-	418.2	133.9	352.4	76.9	164.6

Table 7: Trial 3 Result of Ring Topography

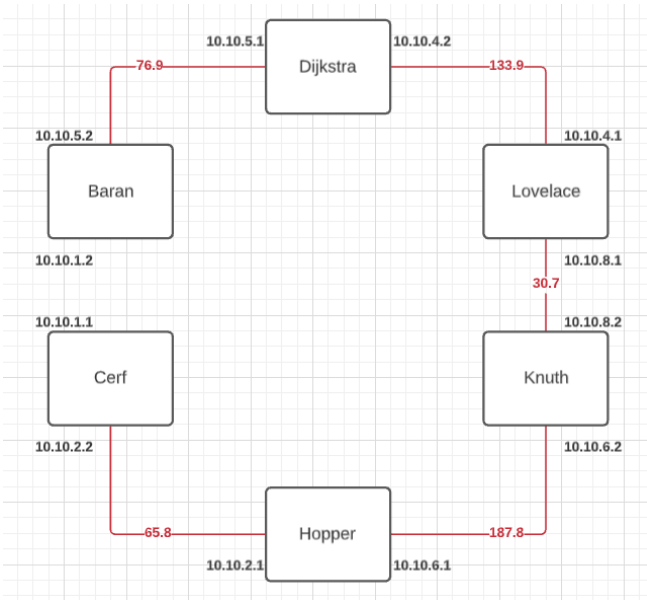


Figure 20: Trial 3 Result of Ring Topography

```
vnnatiell@dijkstra:~$ mtr 10.10.2.2 --report --no-dns
Start: 2021-08-05T13:43:03-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.7 133.9 133.7 134.0 0.1
 2.|-- 10.10.8.2 0.0% 10 164.7 164.6 164.5 164.7 0.0
 3.|-- 10.10.6.1 0.0% 10 352.5 352.4 352.2 352.5 0.1
 4.|-- 10.10.2.2 0.0% 10 418.2 418.2 418.1 418.3 0.1
```

```
vnnatiell@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-08-05T13:37:50-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.8 133.8 133.8 133.9 0.0
```

```
vnnatiell@dijkstra:~$ mtr 10.10.6.1 --report --no-dns
Start: 2021-08-05T13:38:44-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.9 133.9 133.8 134.0 0.0
 2.|-- 10.10.8.2 0.0% 10 164.6 164.6 164.5 164.8 0.1
 3.|-- 10.10.6.1 0.0% 10 352.5 352.5 352.5 352.6 0.1
```

```
vnnatiell@dijkstra:~$ mtr 10.10.5.2 --report --no-dns
Start: 2021-08-05T13:37:22-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.5.2 0.0% 10 76.9 76.9 76.9 77.0 0.0
```

```
vnnatiell@dijkstra:~$ mtr 10.10.8.2 --report --no-dns
Start: 2021-08-05T13:38:14-0400
HOST: dijkstra.finalprojectvn.ch- Loss% Snt Last Avg Best Wrst StDev
 1.|-- 10.10.4.1 0.0% 10 133.8 133.9 133.8 133.9 0.0
 2.|-- 10.10.8.2 0.0% 10 164.7 167.8 164.7 195.5 9.7
```

Figure 21: Trial 3 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 3 found an average transmission cost of 229.2 ms, with the use of 5 links. By removing a link from this topography, the average increase in transmission cost was 57.31 ms, or 11.46 ms per link.

The last topology used was the Fully-Connected topology. The results of each trial were as follows:

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	-	0	-	-	-	-
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	114.747	23.807	95.761	134.775	86.817
2	cerf, hopper, baran, knuth	dijkstra, lovelace	lovelace	-	114.747	23.807	95.761	97.581	76.575
3	cerf, hopper, baran	dijkstra, lovelace, knuth	knuth	-	114.747	23.807	95.761	94.581	76.575
4	cerf, hopper	dijkstra, lovelace, knuth, baran	baran	-	114.747	23.807	95.761	94.581	76.575
5	hopper	dijkstra, lovelace, knuth, cerf	cerf	-	114.747	23.807	95.761	94.581	76.575
6	-	dijkstra, lovelace, knuth, hopper	hopper	-	114.747	23.807	95.761	94.581	76.575

: Trial 1 Result of Fully-Connected Topology

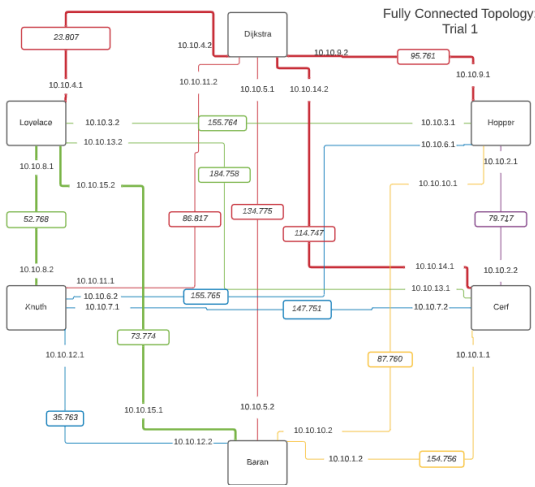


Figure 22: Trial 1 Result of Fully-Connected Topology

```
tristano@dijkstra:~$ mtr 10.10.14.1 --report --no-dns
Start: 2021-07-28T15:37:26-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.14.1 0.0% 10 115.0 114.9 114.7 115.0 0.1

tristano@dijkstra:~$ mtr 10.10.4.1 --report --no-dns
Start: 2021-07-28T15:35:47-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.4.1 0.0% 10 23.9 23.9 23.8 24.0 0.1

tristano@dijkstra:~$ mtr 10.10.9.1 --report --no-dns
Start: 2021-07-28T15:36:40-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.9.1 0.0% 10 95.8 95.9 95.8 96.0 0.1

tristano@dijkstra:~$ mtr 10.10.15.1 --report --no-dns
Start: 2021-07-28T15:17:10-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.4.1 0.0% 10 23.9 23.9 23.8 24.1 0.1
2.|-- 10.10.15.1 0.0% 10 97.5 97.5 97.5 97.7 0.1

tristano@dijkstra:~$ mtr 10.10.8.2 --report --no-dns
Start: 2021-07-28T15:34:52-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.4.1 0.0% 10 23.8 23.9 23.8 23.9 0.0
2.|-- 10.10.8.2 0.0% 10 76.5 76.6 76.4 76.7 0.1
```

Figure 23: Trial 1 mtr results in order of: cerf, lovelace, hopper, baran, knuth

With all nodes connected, the average cost to transmit to any other node was 81.10 ms. This was achieved with the use of 15 links between nodes. The results for trials 2 and 3 are as follows:

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	0	=	=	=	=	=
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	0	114.747	=	95.761	134.775	86.817
2	cerf, hopper, baran, lovelace	dijkstra, knuth	knuth	0	114.747	139.585	95.761	122.58	86.817
3	cerf, hopper, baran	dijkstra, lovelace, knuth	lovelace	0	114.747	139.585	95.761	122.58	86.817
4	cerf, hopper	dijkstra, lovelace, knuth, baran	baran	0	114.747	139.585	95.761	122.58	86.817
5	hopper	dijkstra, lovelace, knuth, cerf	cerf	0	114.747	139.585	95.761	122.58	86.817
6	-	dijkstra, lovelace, knuth, hopper	hopper	0	114.747	139.585	95.761	122.58	86.817

Table 8: Trial 2 Result of Fully-Connected Topology

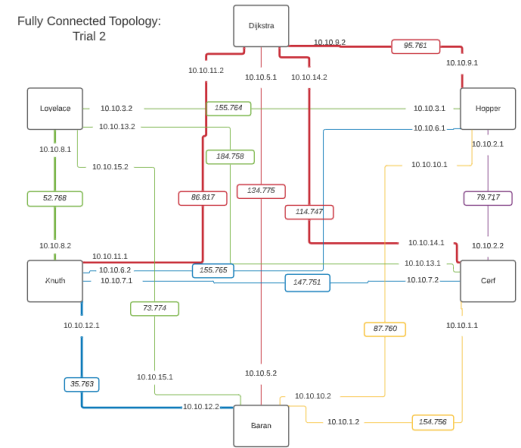


Figure 24: Trial 2 Result of Fully-Connected Topology

```
tristano@dijkstra:~$ mtr 10.10.14.1 --report --no-dns
Start: 2021-07-29T12:17:12-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.14.1 0.0% 10 114.9 114.9 114.8 114.9 0.1

tristano@dijkstra:~$ mtr 10.10.8.1 --report --no-dns
Start: 2021-07-29T12:24:31-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.11.1 0.0% 10 86.8 86.9 86.8 87.0 0.1
2.|-- 10.10.8.1 0.0% 10 139.4 139.6 139.4 139.8 0.1

tristano@dijkstra:~$ mtr 10.10.9.1 --report --no-dns
Start: 2021-07-29T12:10:00-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.9.1 0.0% 10 95.8 95.9 95.8 96.0 0.0

tristano@dijkstra:~$ mtr 10.10.12.2 --report --no-dns
Start: 2021-07-29T12:22:39-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.11.1 0.0% 10 86.9 86.8 86.7 86.9 0.1
2.|-- 10.10.12.2 0.0% 10 122.5 122.4 122.3 122.7 0.1

tristano@dijkstra:~$ mtr 10.10.11.1 --report --no-dns
Start: 2021-07-29T12:23:41-0500
HOST: dijkstra.finalto.ch-geni-ne Loss% Snt Last Avg Best Wrst StDev
1.|-- 10.10.11.1 0.0% 10 86.9 86.9 86.8 87.0 0.0
```

Figure 25: Trial 2 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 2 found an average transmission cost of 111.89 ms, with the use of 14 links.

Iteration	Unvisited	Visited	Current	dijkstra	cerf	lovelace	hopper	baran	knuth
0	dijkstra, cerf, lovelace, hopper, baran, knuth	-	-	-	0	*	*	*	*
1	cerf, lovelace, hopper, baran, knuth	dijkstra	dijkstra	-	0	114.747	23.807	*	134.775
2	cerf, hopper, baran, knuth	dijkstra, lovelace	lovelace	-	0	114.747	23.807	179.571	97.581
3	cerf, hopper, baran	dijkstra, lovelace, knuth	knuth	-	0	114.747	23.807	179.571	94.581
4	cerf, hopper	dijkstra, lovelace, knuth, baran	baran	-	0	114.747	23.807	179.571	94.581
5	hopper	dijkstra, lovelace, knuth, cerf	cerf	-	0	114.747	23.807	179.571	94.581
6	-	dijkstra, lovelace, knuth, hopper	hopper	-	0	114.747	23.807	179.571	94.581

Table 9: Trial 3 Result of Fully-Connected Topology

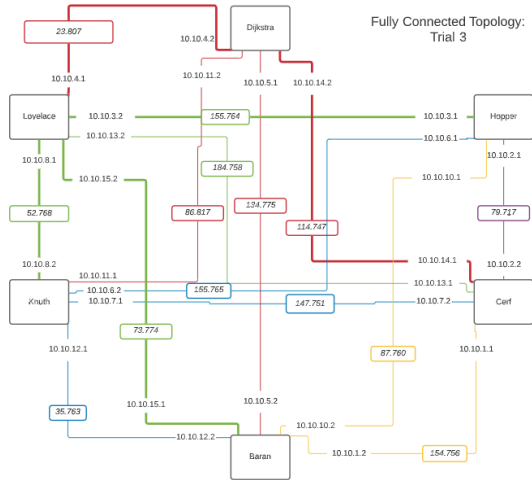


Figure 26: Trial 3 Result of Fully-Connected Topology

Start: 2021-07-29T18:25:10-0500									
HOST: dijkstra.finalto.ch-geni-ne									
1.	--	10.10.14.1	0.0%	10	114.8	114.9	114.8	115.0	0.1
Start: 2021-07-29T18:21:58-0500									
HOST: dijkstra.finalto.ch-geni-ne									
1.	--	10.10.4.1	0.0%	10	23.9	23.9	23.8	24.2	0.1
Start: 2021-07-29T18:25:54-0500									
HOST: dijkstra.finalto.ch-geni-ne									
1.	--	10.10.4.1	0.0%	10	23.8	23.8	23.7	24.0	0.1
2.	--	10.10.3.1	0.0%	10	179.6	179.6	179.5	179.7	0.1
Start: 2021-07-29T18:23:53-0500									
HOST: dijkstra.finalto.ch-geni-ne									
1.	--	10.10.4.1	0.0%	10	23.9	24.0	23.7	25.9	0.7
2.	--	10.10.15.1	0.0%	10	97.7	104.9	97.5	171.0	23.2
Start: 2021-07-29T18:23:05-0500									
HOST: dijkstra.finalto.ch-geni-ne									
1.	--	10.10.4.1	0.0%	10	23.9	23.8	23.7	23.9	0.1
2.	--	10.10.8.2	0.0%	10	76.6	76.6	76.5	76.7	0.1

Figure 27: Trial 3 mtr results in order of: cerf, lovelace, hopper, baran, knuth

Trial 3 found an average transmission cost of 97.86 ms, with the use of 14 links. By removing a link from this topography, the average increase in transmission cost was 23.78 ms, or 1.70 ms per link.

III. CONCLUSION

Overall, this project was very interesting and informative to do. We were able to learn about a few different topologies and the pros and cons of each one. Using PuTTY was straight forward. Making the different routes between nodes and taking down certain connections when required did not take too much effort. Making the topology in GENI was easy as well. The main issue that came was choosing the right site to host it.

There were little to no difficulties when conducting the project. The main issues occurred when trying to set up the GENI slices as sometimes they would fail depending on what site was chosen and would take a lot of time to set up initially. There was also an issue with refreshing nodes that would change the costs causing a need to redo them so the results would be consistent.

For the division of labor, Marla did the mesh topology and its three trials for the experiment. She also wrote the introduction and references for this report. In the powerpoint, she wrote the results and conclusion slides. Vincent did the ring topology and its trials. He also wrote the emulation description. In the powerpoint, he did

the conclusion slide. Tristan did the fully connected topology as well as wrote the abstract and conclusion for this report. He also wrote about the different types of topologies that were covered for the project in the powerpoint. All of us worked on the code file.

REFERENCE

- [1] F. Fund, "Dijkstra's shortest path algorithm," *WITest*, 27-Mar-2017.