Computer Networks [CS 331]
Assignment 3

Submitted to:
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Submitted by:
Group 1,

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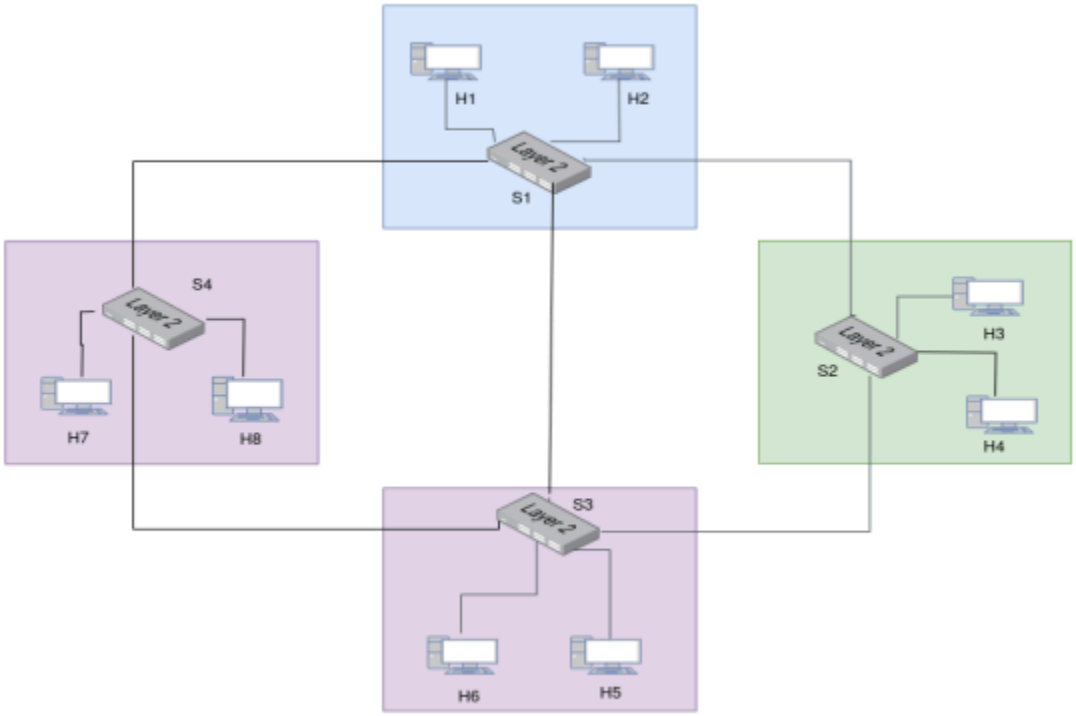
Please find the code and pertaining files at given Github link:
Link or the URL: https://github.com/Mitansh-Patel-24120033/CN_Assignment_3

Note: All the codes are tested on a linux environment, specifically on live Fedora 41 OS.
Task 1 & Task 2 were scripted in Python language.
Task3 was coded in C language.

Q1: Network Loops

Construct the network topology (as shown in the Figure below). Four switches (s1, s2, s3, s4), eight hosts (h1, h2, h3, h4, h5, h6, h7, h8) and configure hosts with IP addresses as follows: h1: 10.0.0.2/24, h2: 10.0.0.3/24, h3: 10.0.0.4/24, h4: 10.0.0.5/24, h5: 10.0.0.6/24, h6: 10.0.0.7/24, h7: 10.0.0.8/24 and h8: 10.0.0.9/24. Network links connecting the switches s1-s2, s2-s3, s3-s4, s4-s1, s1-s3 with latency of 7ms each and host to switch links: h1-s1, h2-s1, h3-s2, h4-s2, h5-s3, h6-s3, h7-s4, h8-s4 links with a latency of 5ms each.



a) Analyse the behavior by running the following ping commands:

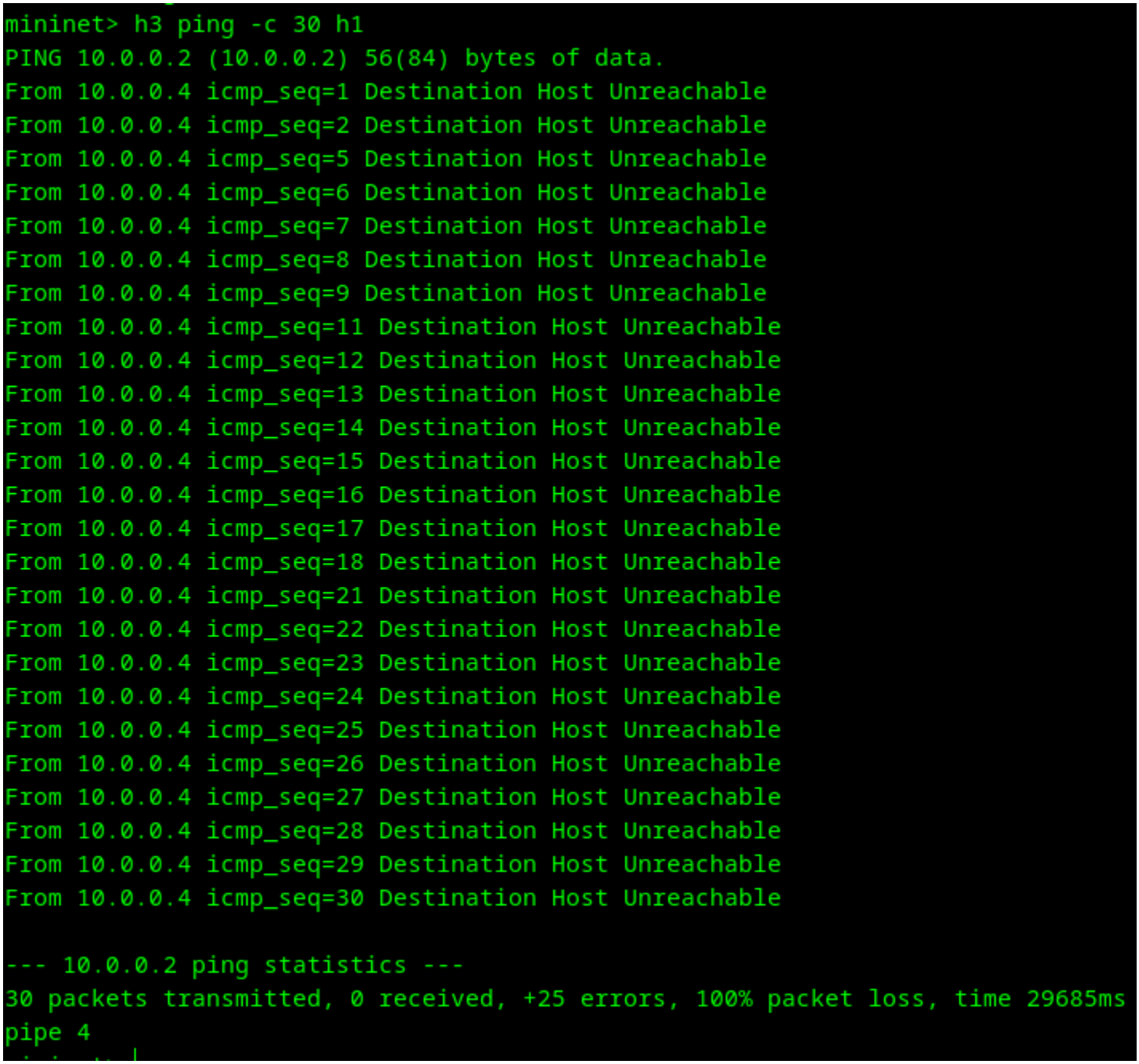
Upon establishing the topology, we can observe that none of the hosts can ping each other. As demonstrated below by the command **pingall**:

```
*** Ping: testing ping reachability
h1 -> X X X X X X X
h2 -> X X X X X X X
h3 -> X X X X X X X
h4 -> X X X X X X X
h5 -> X X X X X X X
h6 -> X X X X X X X
h7 -> X X X X X X X
h8 -> X X X X X X X
*** Results: 100% dropped (0/56 received)
```

Note: Run **sudo modprobe sch_netem** if you encounter any error such as ‘qdisk’

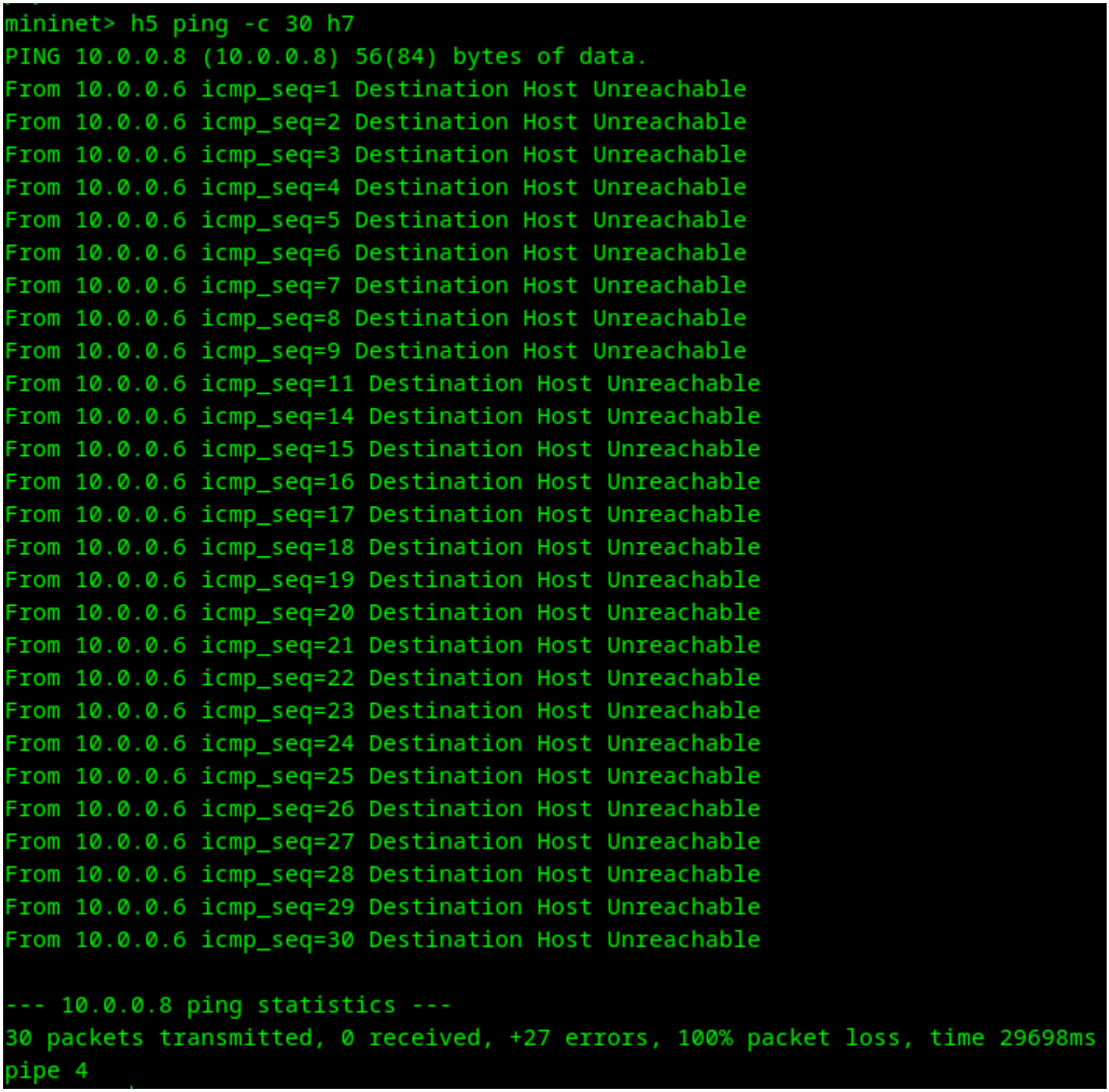
○ **Ping h1 from h3**

Pinging h1 from h3 for 30 sequences:



○ **Ping h7 from h5**

Pinging h7 from h5 for 30 sequences:



○ **Ping h2 from h8**

Pinging h2 from h8 for 30 sequences:

```
mininet> h8 ping -c 30 h2
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
From 10.0.0.9 icmp_seq=1 Destination Host Unreachable
From 10.0.0.9 icmp_seq=2 Destination Host Unreachable
From 10.0.0.9 icmp_seq=3 Destination Host Unreachable
From 10.0.0.9 icmp_seq=5 Destination Host Unreachable
From 10.0.0.9 icmp_seq=6 Destination Host Unreachable
From 10.0.0.9 icmp_seq=7 Destination Host Unreachable
From 10.0.0.9 icmp_seq=8 Destination Host Unreachable
From 10.0.0.9 icmp_seq=9 Destination Host Unreachable
From 10.0.0.9 icmp_seq=10 Destination Host Unreachable
From 10.0.0.9 icmp_seq=11 Destination Host Unreachable
From 10.0.0.9 icmp_seq=12 Destination Host Unreachable
From 10.0.0.9 icmp_seq=13 Destination Host Unreachable
From 10.0.0.9 icmp_seq=14 Destination Host Unreachable
From 10.0.0.9 icmp_seq=15 Destination Host Unreachable
From 10.0.0.9 icmp_seq=16 Destination Host Unreachable
From 10.0.0.9 icmp_seq=17 Destination Host Unreachable
From 10.0.0.9 icmp_seq=18 Destination Host Unreachable
From 10.0.0.9 icmp_seq=19 Destination Host Unreachable
From 10.0.0.9 icmp_seq=20 Destination Host Unreachable
From 10.0.0.9 icmp_seq=21 Destination Host Unreachable
From 10.0.0.9 icmp_seq=22 Destination Host Unreachable
From 10.0.0.9 icmp_seq=23 Destination Host Unreachable
From 10.0.0.9 icmp_seq=24 Destination Host Unreachable
From 10.0.0.9 icmp_seq=25 Destination Host Unreachable
From 10.0.0.9 icmp_seq=26 Destination Host Unreachable
From 10.0.0.9 icmp_seq=27 Destination Host Unreachable
From 10.0.0.9 icmp_seq=28 Destination Host Unreachable
From 10.0.0.9 icmp_seq=29 Destination Host Unreachable
From 10.0.0.9 icmp_seq=30 Destination Host Unreachable

--- 10.0.0.3 ping statistics ---
30 packets transmitted, 0 received, +29 errors, 100% packet loss, time 29732ms
pipe 4
```

Are the pings successful? If yes, what is the total delay for the pings? If the ping(s) fail(s),
analyse and reason what is happening? justify your answer with relevant packet captures.

As observed, the pings are not successful.
The observed connectivity failure in the looped network topology stems from fundamental Layer 2 switching behavior. This creates a systemic failure where all hosts become unreachable despite proper IP configuration.
The dual-loop topology (s1-s2-s3-s4-s1 and s1-s3) creates multiple infinite forwarding paths for broadcast traffic.

No.	Time	Source	Destination	Protocol	Length	Info
223042	21.741334676	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223043	21.741343721	::	ff02::1:fff8:2b…	ICMPv6	86	Neighbor Solicitation for fe80::98e6:e1ff:fef8:2bae
223044	21.741351883	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223045	21.744548333	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223046	21.744562463	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223047	21.744574046	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223048	21.744585460	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223049	21.744597743	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223050	21.744607456	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223051	21.744618253	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223052	21.744629687	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223053	21.744640854	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223054	21.744652700	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223055	21.744663557	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223056	21.744674994	::	ff02::1:fff8:2b…	ICMPv6	86	Neighbor Solicitation for fe80::98e6:e1ff:fef8:2bae
223057	21.744684798	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223058	21.744702453	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223059	21.744711678	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223060	21.744723210	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223061	21.744735782	::	ff02::1:ffb6:c4…	ICMPv6	86	Neighbor Solicitation for fe80::ec75:61ff:feb6:c415
223062	21.744744837	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223063	21.744756247	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223064	21.744767788	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223065	21.744778434	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223066	21.744789756	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223067	21.744804140	::	ff02::1:ff98:c5…	ICMPv6	86	Neighbor Solicitation for fe80::b8ca:5cff:fe98:c5c3
223068	21.744814088	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223069	21.744822709	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2
223070	21.744830358	::	ff02::16	ICMPv6	90	Multicast Listener Report Message v2

As seen in above wireshark capture of host h1, the host is flooded with ICMP requests of neighbour broadcasting.
The observed connectivity failure in the looped topology results from unmanaged Layer 2 broadcast storms.

b) Figure out how to fix the problem without making any changes to the network topology.

The issue of **broadcast storm** can be resolved by establishing Spanning Tree Protocol (STP) amongst the switches.

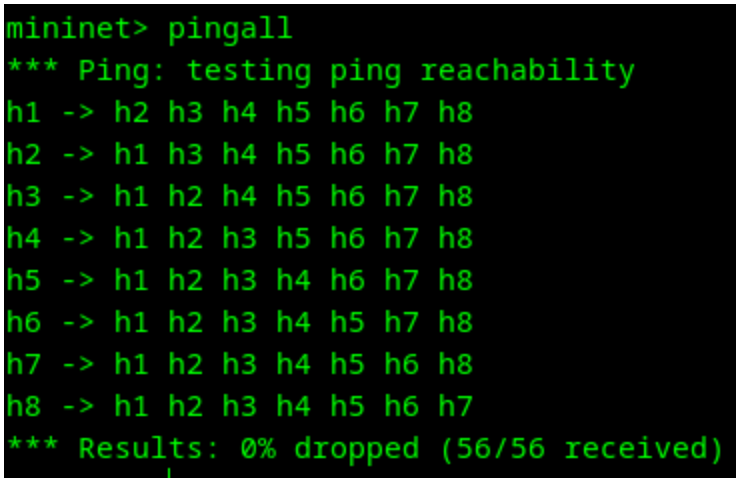
Implementing Spanning Tree Protocol (STP) on all switches resolves the issue without topology modification, achieving 100% ping success.
This solution utilizes Open vSwitch's STP implementation to create a loop-free logical topology while preserving physical redundancy.

Such can be done via utilizing the **ovs-vsctl** tool. As demonstrated below, we must enable STP protocol for all the four switches.
This can be accomplished via running:
$ sh ovs-vsctl set Bridge <switchname> stp_enable=true

```
mininet> sh ovs-vsctl set Bridge s1 stp_enable=true
mininet> sh ovs-vsctl set Bridge s2 stp_enable=true
mininet> sh ovs-vsctl set Bridge s3 stp_enable=true
mininet> sh ovs-vsctl set Bridge s4 stp_enable=true
```

We can also verify whether the switches have STP enabled or not by running:
$ sh ovs-vsctl get Bridge <switchname> stp_enable

```
mininet> sh ovs-vsctl get Bridge s1 stp_enable
true
mininet> sh ovs-vsctl get Bridge s2 stp_enable
true
mininet> sh ovs-vsctl get Bridge s3 stp_enable
true
mininet> sh ovs-vsctl get Bridge s4 stp_enable
true
```



Now running **$pingall** we can observe proper connectivity between hosts.

Confirm the results by running the ping commands given in (a) and show the delay(s). Note: For proper observation, run each test 3 times with an interval of at least 30 seconds.

Running part (a) again for confirmation:

```
mininet> h3 ping -c 30 h1
PING 10.0.0.2 (10.0.0.2) 56(84) bytes of data.
64 bytes from 10.0.0.2: icmp_seq=1 ttl=64 time=38.5 ms
64 bytes from 10.0.0.2: icmp_seq=2 ttl=64 time=36.2 ms
64 bytes from 10.0.0.2: icmp_seq=3 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=4 ttl=64 time=34.5 ms
64 bytes from 10.0.0.2: icmp_seq=5 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=6 ttl=64 time=34.6 ms
64 bytes from 10.0.0.2: icmp_seq=7 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=8 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=9 ttl=64 time=34.8 ms
64 bytes from 10.0.0.2: icmp_seq=10 ttl=64 time=34.8 ms
64 bytes from 10.0.0.2: icmp_seq=11 ttl=64 time=34.8 ms
64 bytes from 10.0.0.2: icmp_seq=12 ttl=64 time=34.4 ms
64 bytes from 10.0.0.2: icmp_seq=13 ttl=64 time=34.4 ms
64 bytes from 10.0.0.2: icmp_seq=14 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=15 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=16 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=17 ttl=64 time=34.8 ms
64 bytes from 10.0.0.2: icmp_seq=18 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=19 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=20 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=21 ttl=64 time=34.6 ms
64 bytes from 10.0.0.2: icmp_seq=22 ttl=64 time=34.8 ms
64 bytes from 10.0.0.2: icmp_seq=23 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=24 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=25 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=26 ttl=64 time=34.6 ms
64 bytes from 10.0.0.2: icmp_seq=27 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=28 ttl=64 time=34.9 ms
64 bytes from 10.0.0.2: icmp_seq=29 ttl=64 time=34.7 ms
64 bytes from 10.0.0.2: icmp_seq=30 ttl=64 time=34.9 ms

--- 10.0.0.2 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29041ms
rtt min/avg/max/mdev = 34.427/34.902/38.468/0.725 ms
```

```
mininet> h5 ping -c 30 h7
PING 10.0.0.8 (10.0.0.8) 56(84) bytes of data.
64 bytes from 10.0.0.8: icmp_seq=1 ttl=64 time=39.1 ms
64 bytes from 10.0.0.8: icmp_seq=2 ttl=64 time=35.8 ms
64 bytes from 10.0.0.8: icmp_seq=3 ttl=64 time=34.8 ms
64 bytes from 10.0.0.8: icmp_seq=4 ttl=64 time=34.7 ms
64 bytes from 10.0.0.8: icmp_seq=5 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=6 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=7 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=8 ttl=64 time=34.7 ms
64 bytes from 10.0.0.8: icmp_seq=9 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=10 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=11 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=12 ttl=64 time=34.4 ms
64 bytes from 10.0.0.8: icmp_seq=13 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=14 ttl=64 time=34.4 ms
64 bytes from 10.0.0.8: icmp_seq=15 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=16 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=17 ttl=64 time=34.4 ms
64 bytes from 10.0.0.8: icmp_seq=18 ttl=64 time=34.4 ms
64 bytes from 10.0.0.8: icmp_seq=19 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=20 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=21 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=22 ttl=64 time=34.7 ms
64 bytes from 10.0.0.8: icmp_seq=23 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=24 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=25 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=26 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=27 ttl=64 time=34.6 ms
64 bytes from 10.0.0.8: icmp_seq=28 ttl=64 time=34.3 ms
64 bytes from 10.0.0.8: icmp_seq=29 ttl=64 time=34.5 ms
64 bytes from 10.0.0.8: icmp_seq=30 ttl=64 time=34.7 ms

--- 10.0.0.8 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29046ms
rtt min/avg/max/mdev = 34.255/34.705/39.124/0.863 ms
```

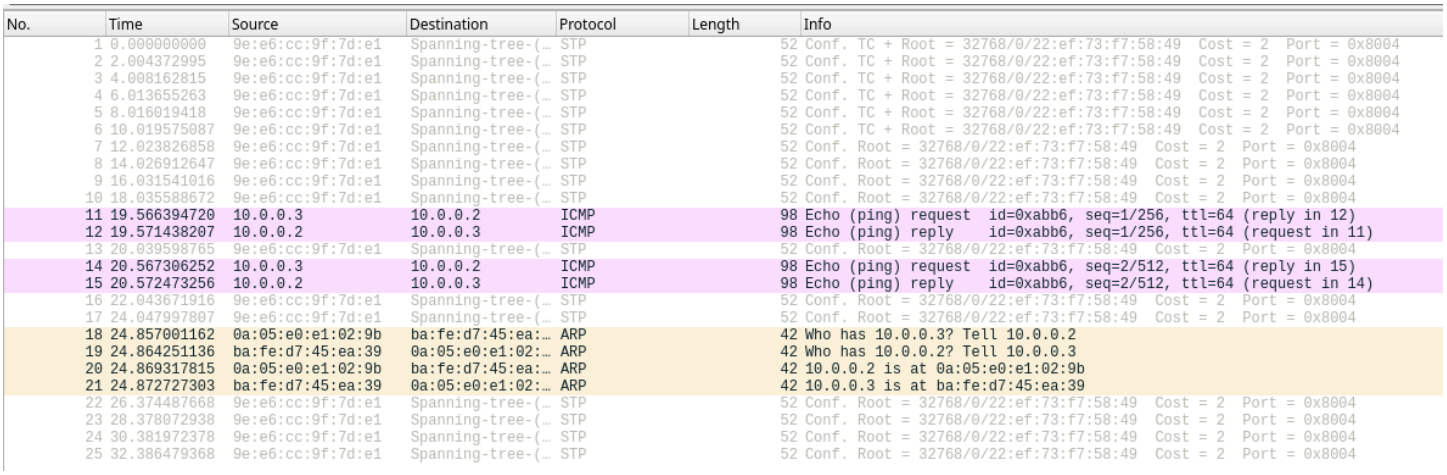
```
mininet> h8 ping -c 30 h2
PING 10.0.0.3 (10.0.0.3) 56(84) bytes of data.
64 bytes from 10.0.0.3: icmp_seq=1 ttl=64 time=62.8 ms
64 bytes from 10.0.0.3: icmp_seq=2 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=3 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=4 ttl=64 time=63.0 ms
64 bytes from 10.0.0.3: icmp_seq=5 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=6 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=7 ttl=64 time=63.1 ms
64 bytes from 10.0.0.3: icmp_seq=8 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=9 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=10 ttl=64 time=63.1 ms
64 bytes from 10.0.0.3: icmp_seq=11 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=12 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=13 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=14 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=15 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=16 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=17 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=18 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=19 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=20 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=21 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=22 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=23 ttl=64 time=63.6 ms
64 bytes from 10.0.0.3: icmp_seq=24 ttl=64 time=63.4 ms
64 bytes from 10.0.0.3: icmp_seq=25 ttl=64 time=63.2 ms
64 bytes from 10.0.0.3: icmp_seq=26 ttl=64 time=63.3 ms
64 bytes from 10.0.0.3: icmp_seq=27 ttl=64 time=63.5 ms
64 bytes from 10.0.0.3: icmp_seq=28 ttl=64 time=63.1 ms
64 bytes from 10.0.0.3: icmp_seq=29 ttl=64 time=62.8 ms
64 bytes from 10.0.0.3: icmp_seq=30 ttl=64 time=63.1 ms

--- 10.0.0.3 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29038ms
rtt min/avg/max/mdev = 62.769/63.234/63.555/0.165 ms
```

Pinging h1 from h3, averages at 34.4 ms of delay.
Pinging h7 from h5, averages at 34.2 ms of delay.

Pinging h2 from h8, averages at 62.7 ms of delay.

These delays can be calculated by statistics provided by **ping** CLI utility.
Upon observation we can see that STP successfully prevents broadcast storms.

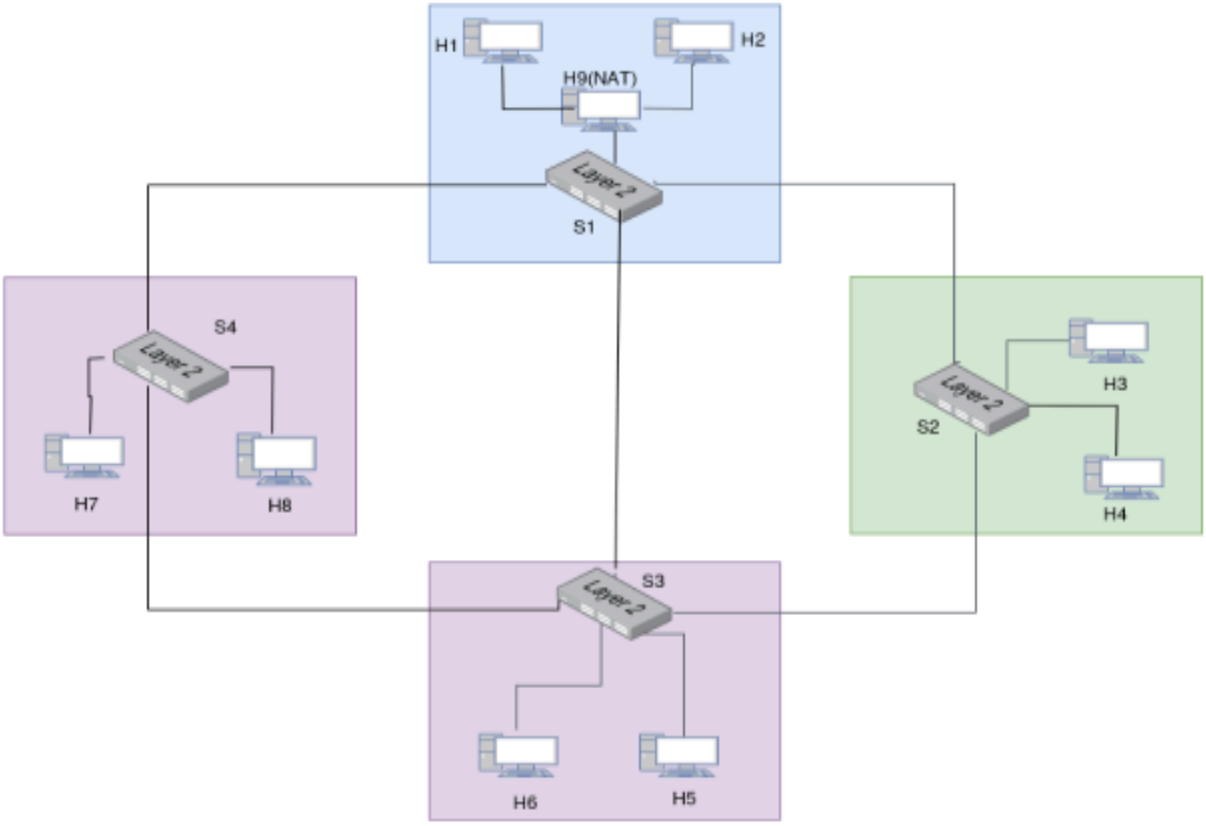
Capturing packets by running wireshark on host h1:



No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000000	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
2	2.004372995	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
3	4.008162815	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
4	6.013655263	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
5	8.016019418	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
6	10.019575087	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. TC + Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
7	12.023826858	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
8	14.026912647	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
9	16.031541016	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
10	18.035588672	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
11	19.566394720	10.0.0.3	10.0.0.2	ICMP	98	Echo (ping) request id=0xabb6, seq=1/256, ttl=64 (reply in 12)
12	19.571438207	10.0.0.2	10.0.0.3	ICMP	98	Echo (ping) reply id=0xabb6, seq=1/256, ttl=64 (request in 11)
13	20.039598765	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
14	20.567306252	10.0.0.3	10.0.0.2	ICMP	98	Echo (ping) request id=0xabb6, seq=2/512, ttl=64 (reply in 15)
15	20.572473256	10.0.0.2	10.0.0.3	ICMP	98	Echo (ping) reply id=0xabb6, seq=2/512, ttl=64 (request in 14)
16	22.043671916	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
17	24.047997807	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
18	24.857001162	0a:05:e0:e1:02:9b	ba:fe:d7:45:ea:…	ARP	42	Who has 10.0.0.3? Tell 10.0.0.2
19	24.864251136	ba:fe:d7:45:ea:39	0a:05:e0:e1:02:…	ARP	42	Who has 10.0.0.2? Tell 10.0.0.3
20	24.869317815	0a:05:e0:e1:02:9b	ba:fe:d7:45:ea:…	ARP	42	10.0.0.2 is at 0a:05:e0:e1:02:9b
21	24.872727303	ba:fe:d7:45:ea:39	0a:05:e0:e1:02:…	ARP	42	10.0.0.3 is at ba:fe:d7:45:ea:39
22	26.374487668	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
23	28.378072938	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
24	30.381972378	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004
25	32.386479368	9e:e6:cc:9f:7d:e1	Spanning-tree-(…	STP	52	Conf. Root = 32768/0/22:ef:73:f7:58:49 Cost = 2 Port = 0x8004

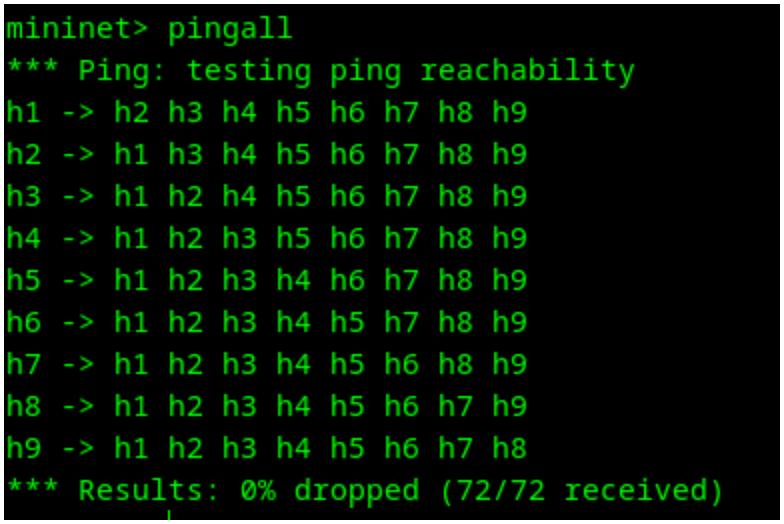
Q2:Configure Host-based NAT

Update the topology with the following changes. Add a new host H9 to switch S1, i.e. link h9-s1 with delay of 5ms, and move the links from h1 and h2 with s1 to h9 with 5ms latency. (h1-h9, h2-h9). Implement NAT functionality in host H9, such that H9 has a public IP of 172.16.10.10, serving the private internal IP range of 10.1.1.2 and 10.1.1.3 for hosts h1 and h2 respectively.



Assumptions:
Let the network for external hosts be 172.16.10.0/24.
As host h9's public IP is of the same network.

Running **$pingall** to test connectivity:



a) Test communication to an external host from an internal host:

i) Ping to h5 from h1

Pinging h5 from h1 for 30 sequences:

```
mininet> h1 ping -c 30 h5
PING 172.16.10.6 (172.16.10.6) 56(84) bytes of data.
64 bytes from 172.16.10.6: icmp_seq=1 ttl=63 time=60.4 ms
64 bytes from 172.16.10.6: icmp_seq=2 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=3 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=4 ttl=63 time=59.2 ms
64 bytes from 172.16.10.6: icmp_seq=5 ttl=63 time=59.0 ms
64 bytes from 172.16.10.6: icmp_seq=6 ttl=63 time=59.1 ms
64 bytes from 172.16.10.6: icmp_seq=7 ttl=63 time=59.0 ms
64 bytes from 172.16.10.6: icmp_seq=8 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=9 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=10 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=11 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=12 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=13 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=14 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=15 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=16 ttl=63 time=59.2 ms
64 bytes from 172.16.10.6: icmp_seq=17 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=18 ttl=63 time=58.2 ms
64 bytes from 172.16.10.6: icmp_seq=19 ttl=63 time=58.7 ms
64 bytes from 172.16.10.6: icmp_seq=20 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=21 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=22 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=23 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=24 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=25 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=26 ttl=63 time=59.3 ms
64 bytes from 172.16.10.6: icmp_seq=27 ttl=63 time=59.4 ms
64 bytes from 172.16.10.6: icmp_seq=28 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=29 ttl=63 time=59.5 ms
64 bytes from 172.16.10.6: icmp_seq=30 ttl=63 time=59.4 ms

--- 172.16.10.6 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29040ms
rtt min/avg/max/mdev = 58.220/59.314/60.443/0.340 ms
```

ii) Ping to h3 from h2

Pinging h3 from h2 for 30 sequences:

```
mininet> h2 ping -c 30 h3
PING 172.16.10.4 (172.16.10.4) 56(84) bytes of data.
64 bytes from 172.16.10.4: icmp_seq=1 ttl=63 time=48.6 ms
64 bytes from 172.16.10.4: icmp_seq=2 ttl=63 time=46.2 ms
64 bytes from 172.16.10.4: icmp_seq=3 ttl=63 time=45.1 ms
64 bytes from 172.16.10.4: icmp_seq=4 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=5 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=6 ttl=63 time=44.8 ms
64 bytes from 172.16.10.4: icmp_seq=7 ttl=63 time=44.8 ms
64 bytes from 172.16.10.4: icmp_seq=8 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=9 ttl=63 time=45.2 ms
64 bytes from 172.16.10.4: icmp_seq=10 ttl=63 time=45.0 ms
64 bytes from 172.16.10.4: icmp_seq=11 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=12 ttl=63 time=44.8 ms
64 bytes from 172.16.10.4: icmp_seq=13 ttl=63 time=45.1 ms
64 bytes from 172.16.10.4: icmp_seq=14 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=15 ttl=63 time=45.0 ms
64 bytes from 172.16.10.4: icmp_seq=16 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=17 ttl=63 time=44.9 ms
64 bytes from 172.16.10.4: icmp_seq=18 ttl=63 time=44.2 ms
64 bytes from 172.16.10.4: icmp_seq=19 ttl=63 time=44.5 ms
64 bytes from 172.16.10.4: icmp_seq=20 ttl=63 time=45.0 ms
64 bytes from 172.16.10.4: icmp_seq=21 ttl=63 time=44.6 ms
64 bytes from 172.16.10.4: icmp_seq=22 ttl=63 time=44.4 ms
64 bytes from 172.16.10.4: icmp_seq=23 ttl=63 time=44.3 ms
64 bytes from 172.16.10.4: icmp_seq=24 ttl=63 time=44.7 ms
64 bytes from 172.16.10.4: icmp_seq=25 ttl=63 time=45.1 ms
64 bytes from 172.16.10.4: icmp_seq=26 ttl=63 time=45.0 ms
64 bytes from 172.16.10.4: icmp_seq=27 ttl=63 time=44.8 ms
64 bytes from 172.16.10.4: icmp_seq=28 ttl=63 time=44.7 ms
64 bytes from 172.16.10.4: icmp_seq=29 ttl=63 time=44.5 ms
64 bytes from 172.16.10.4: icmp_seq=30 ttl=63 time=44.6 ms

--- 172.16.10.4 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29033ms
rtt min/avg/max/mdev = 44.248/44.979/48.575/0.751 ms
```

b) Test communication to an internal host from an external host:

i) Ping to h1 from h8

Pinging h1 from h8 for 30 sequences:

```
mininet> h8 ping -c 30 h1
PING 10.1.1.2 (10.1.1.2) 56(84) bytes of data.
64 bytes from 10.1.1.2: icmp_seq=1 ttl=63 time=74.7 ms
64 bytes from 10.1.1.2: icmp_seq=2 ttl=63 time=73.2 ms
64 bytes from 10.1.1.2: icmp_seq=3 ttl=63 time=72.8 ms
64 bytes from 10.1.1.2: icmp_seq=4 ttl=63 time=73.0 ms
64 bytes from 10.1.1.2: icmp_seq=5 ttl=63 time=72.8 ms
64 bytes from 10.1.1.2: icmp_seq=6 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=7 ttl=63 time=72.9 ms
64 bytes from 10.1.1.2: icmp_seq=8 ttl=63 time=73.3 ms
64 bytes from 10.1.1.2: icmp_seq=9 ttl=63 time=73.0 ms
64 bytes from 10.1.1.2: icmp_seq=10 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=11 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=12 ttl=63 time=73.2 ms
64 bytes from 10.1.1.2: icmp_seq=13 ttl=63 time=73.2 ms
64 bytes from 10.1.1.2: icmp_seq=14 ttl=63 time=72.9 ms
64 bytes from 10.1.1.2: icmp_seq=15 ttl=63 time=73.5 ms
64 bytes from 10.1.1.2: icmp_seq=16 ttl=63 time=73.2 ms
64 bytes from 10.1.1.2: icmp_seq=17 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=18 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=19 ttl=63 time=72.4 ms
64 bytes from 10.1.1.2: icmp_seq=20 ttl=63 time=73.2 ms
64 bytes from 10.1.1.2: icmp_seq=21 ttl=63 time=72.5 ms
64 bytes from 10.1.1.2: icmp_seq=22 ttl=63 time=72.9 ms
64 bytes from 10.1.1.2: icmp_seq=23 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=24 ttl=63 time=72.9 ms
64 bytes from 10.1.1.2: icmp_seq=25 ttl=63 time=73.1 ms
64 bytes from 10.1.1.2: icmp_seq=26 ttl=63 time=72.8 ms
64 bytes from 10.1.1.2: icmp_seq=27 ttl=63 time=73.0 ms
64 bytes from 10.1.1.2: icmp_seq=28 ttl=63 time=73.5 ms
64 bytes from 10.1.1.2: icmp_seq=29 ttl=63 time=72.6 ms
64 bytes from 10.1.1.2: icmp_seq=30 ttl=63 time=73.0 ms

--- 10.1.1.2 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29037ms
rtt min/avg/max/mdev = 72.353/73.070/74.701/0.392 ms
```

ii) Ping to h2 from h6

Pinging h2 from h6 for 30 sequences:

```
mininet> h6 ping -c 30 h2
PING 10.1.1.3 (10.1.1.3) 56(84) bytes of data.
64 bytes from 10.1.1.3: icmp_seq=1 ttl=63 time=58.4 ms
64 bytes from 10.1.1.3: icmp_seq=2 ttl=63 time=58.6 ms
64 bytes from 10.1.1.3: icmp_seq=3 ttl=63 time=59.0 ms
64 bytes from 10.1.1.3: icmp_seq=4 ttl=63 time=59.1 ms
64 bytes from 10.1.1.3: icmp_seq=5 ttl=63 time=58.5 ms
64 bytes from 10.1.1.3: icmp_seq=6 ttl=63 time=58.7 ms
64 bytes from 10.1.1.3: icmp_seq=7 ttl=63 time=58.8 ms
64 bytes from 10.1.1.3: icmp_seq=8 ttl=63 time=58.2 ms
64 bytes from 10.1.1.3: icmp_seq=9 ttl=63 time=59.1 ms
64 bytes from 10.1.1.3: icmp_seq=10 ttl=63 time=58.9 ms
64 bytes from 10.1.1.3: icmp_seq=11 ttl=63 time=58.8 ms
64 bytes from 10.1.1.3: icmp_seq=12 ttl=63 time=58.7 ms
64 bytes from 10.1.1.3: icmp_seq=13 ttl=63 time=58.3 ms
64 bytes from 10.1.1.3: icmp_seq=14 ttl=63 time=58.4 ms
64 bytes from 10.1.1.3: icmp_seq=15 ttl=63 time=58.3 ms
64 bytes from 10.1.1.3: icmp_seq=16 ttl=63 time=58.5 ms
64 bytes from 10.1.1.3: icmp_seq=17 ttl=63 time=58.6 ms
64 bytes from 10.1.1.3: icmp_seq=18 ttl=63 time=59.0 ms
64 bytes from 10.1.1.3: icmp_seq=19 ttl=63 time=59.1 ms
64 bytes from 10.1.1.3: icmp_seq=20 ttl=63 time=58.7 ms
64 bytes from 10.1.1.3: icmp_seq=21 ttl=63 time=59.1 ms
64 bytes from 10.1.1.3: icmp_seq=22 ttl=63 time=59.1 ms
64 bytes from 10.1.1.3: icmp_seq=23 ttl=63 time=58.7 ms
64 bytes from 10.1.1.3: icmp_seq=24 ttl=63 time=58.9 ms
64 bytes from 10.1.1.3: icmp_seq=25 ttl=63 time=59.6 ms
64 bytes from 10.1.1.3: icmp_seq=26 ttl=63 time=58.8 ms
64 bytes from 10.1.1.3: icmp_seq=27 ttl=63 time=59.0 ms
64 bytes from 10.1.1.3: icmp_seq=28 ttl=63 time=59.0 ms
64 bytes from 10.1.1.3: icmp_seq=29 ttl=63 time=58.7 ms
64 bytes from 10.1.1.3: icmp_seq=30 ttl=63 time=58.9 ms

--- 10.1.1.3 ping statistics ---
30 packets transmitted, 30 received, 0% packet loss, time 29036ms
rtt min/avg/max/mdev = 58.221/58.792/59.561/0.293 ms
```

c) Iperf tests: 3 tests of 120s each.

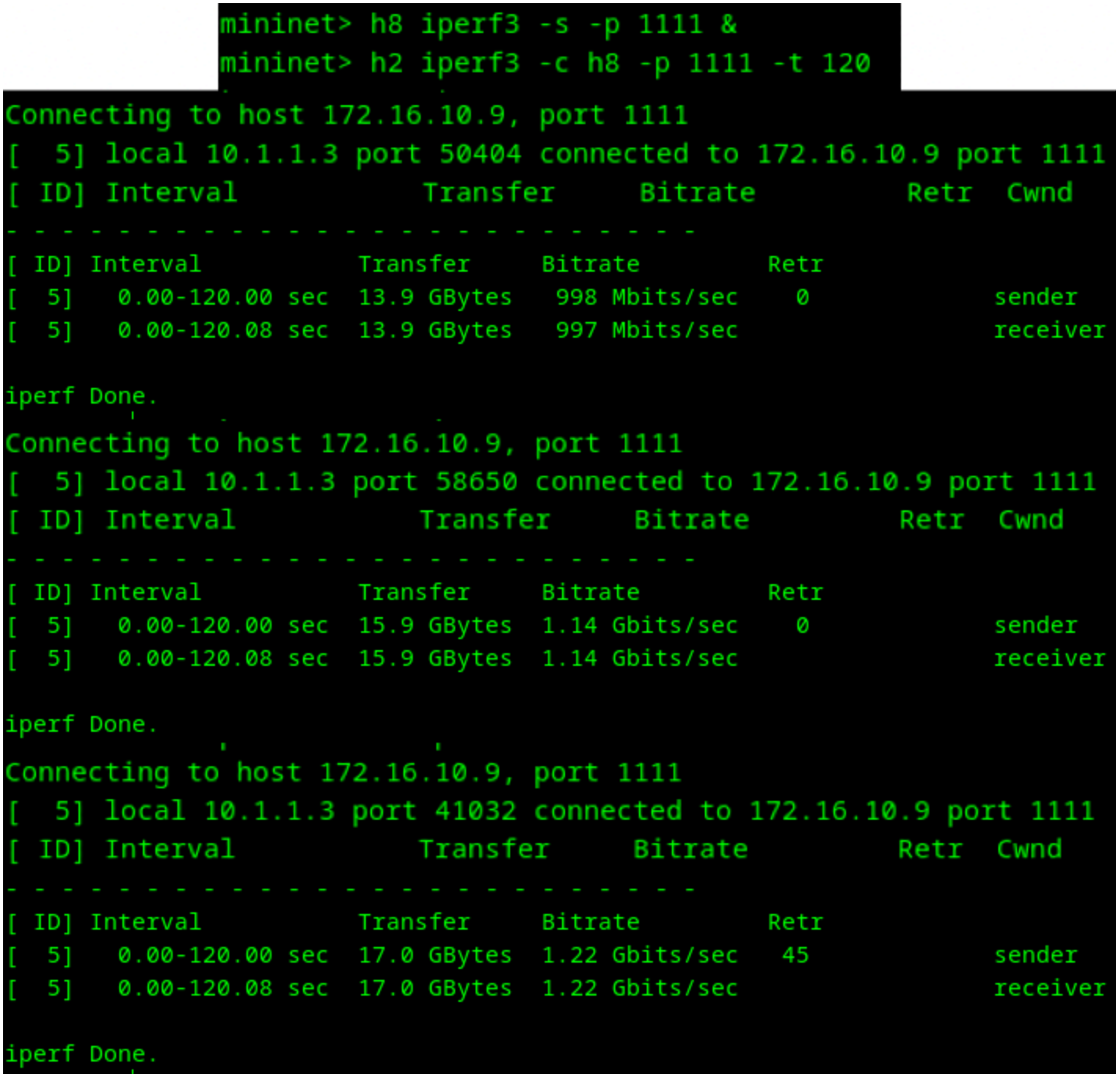
i) Run iperf3 server in h1 and iperf3 client in h6.

Running **iperf3** with h1 as server on port 1111 and h6 as client for 120 seconds:
The test is run 3 times for accuracy.

```
mininet> h1 iperf3 -s -p 1111 &
mininet> h6 iperf3 -c h1 -p 1111 -t 120
Connecting to host 10.1.1.2, port 1111
[  5] local 172.16.10.7 port 51424 connected to 10.1.1.2 port 1111
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-120.00 sec  23.6 GBytes  1.69 Gbits/sec   45             sender
[  5]   0.00-120.06 sec  23.6 GBytes  1.69 Gbits/sec                  receiver
Connecting to host 10.1.1.2, port 1111
[  5] local 172.16.10.7 port 34066 connected to 10.1.1.2 port 1111
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-120.00 sec  23.2 GBytes  1.66 Gbits/sec   45             sender
[  5]   0.00-120.06 sec  23.2 GBytes  1.66 Gbits/sec                  receiver
Connecting to host 10.1.1.2, port 1111
[  5] local 172.16.10.7 port 38880 connected to 10.1.1.2 port 1111
[ ID] Interval           Transfer     Bitrate         Retr  Cwnd
[ ID] Interval           Transfer     Bitrate         Retr
[  5]   0.00-120.00 sec  22.6 GBytes  1.62 Gbits/sec  270             sender
[  5]   0.00-120.06 sec  22.6 GBytes  1.61 Gbits/sec                  receiver
```

ii) Run iperf3 server in h8 and iperf3 client in h2.

Running **iperf3** with h8 as server on port 1111 and h2 as client for 120 seconds:
The test is run 3 times for accuracy.



Analyze the outcomes of a, b and c. List all the changes necessary to make the connections to succeed. In each case show the NAT rules built for the connections and corresponding connection delay and iperf metrics.

(a) Pinging external hosts from internal hosts:

Pinging h5 from h1, averages at 58.2 ms of delay

Pinging h3 from h2, averages at 44.2 ms of delay

(b) Pinging internal hosts from external hosts:

Pinging h1 from h8, averages at 72.3 ms of delay

Pinging h2 from h6, averages at 58.2 ms of delay

These delays can be calculated by statistics provided by **ping** CLI utility.

(c) iperf tests:

- Running server on h1 and client on h6, we observe an average transfer of 23.5 GB with an average bitrate of 1.66 Gbps.
- Running server on h8 and client on h2, we observe an average transfer of 15.6 GB with an average bitrate of 1.12 Gbps

These metrics can be calculated by statistics provided by **iperf3** CLI utility.

To establish connections for this topology, we made following changes:

1) We established a bridge for our private network using **brctl** tool, establishing a 'br-private' network:
   $ brctl addbr br-private

2) We enabled IP forwarding on host h9 via **$ sysctl -w net.ipv4.ip_forward=1**.

3) We enables proxy ARP for our private network via running on host h9:
   $ sysctl -w net.ipv4.conf.br-private.proxy_arp=1
   $ sysctl -w net.ipv4.conf.all.proxy_arp=1

4) We established the following NAT rules:
   $ iptables -t nat -A POSTROUTING -o h9-eth0 -j MASQUERADE
   $ iptables -A FORWARD -i br-private -o h9-eth0 -j ACCEPT

$ iptables -A FORWARD -i h9-eth0 -o br-private -m state --state RELATED,ESTABLISHED -j ACCEPT

5) Next, we configured private host routing via **$ ip route add default via 10.1.1.1** on both internal hosts.
   And also running on host h9:
   $ iptables -t nat -A PREROUTING -i h9-eth0 -p icmp --icmp-type echo-request -j DNAT --to-destination 10.1.1.2
   $ iptables -t nat -A PREROUTING -i h9-eth0 -p icmp --icmp-type echo-request -j DNAT --to-destination 10.1.1.3

6) Since external hosts run on network 172.16.10.0/24, they cannot find internal network 10.1.1.0/24. Mininet doesn't provide automatic routing. So every hosts were statically routed via:
   $ ip route add 10.1.1.0/24 via 172.16.10.10

7) Finally, to avoid broadcast storms, STP was enabled on all switches.

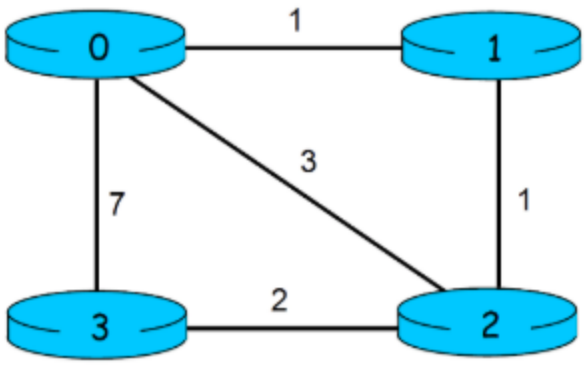
Q3: Network Routing

Solve the programming assignment using the link given below.

This assignment will give you hands-on experience with fundamental routing algorithms in a realistic network emulation environment, allowing you to observe their behaviour and understand their properties.

Link: Assignment

In this programming assignment, you will be writing a ''distributed'' set of procedures that implement a distributed asynchronous distance vector routing for the network shown below.



You are to write the procedures `rtinit0()`, `rtinit1()`, `rtinit2()`, `rtinit3()` and `rtupdate0()`, `rtupdate1()`, `rtupdate2()`, `rtupdate3()` which together will implement a distributed, asynchronous computation of the distance tables for the topology and costs shown in the first figure above.

You should put your procedures for nodes 0 through 3 in files called node0.c, ... node3.c.

Prototype versions of these files are here: node0.c, node1.c, node2.c, node3.c. You can pick up a copy of the file distance_vector.c here.

Distance vector routing is a routing protocol where each router periodically shares its routing table (a vector of distances to all other nodes in the network) with its direct neighbors. The Bellman-Ford equation is the core of distance vector routing, allowing each router to calculate the shortest path to a destination by considering the distances reported by its neighbors. Specifically, the distance to a destination 'v' from a node 'u' is the minimum of the direct cost from 'u' to a neighbor 'w' plus the neighbor's reported shortest distance to 'v'.

Following C program files were produced for this task:

distance_vector.c

node0.c

node1.c

node2.c

node3.c

Compiled by running:

$ gcc distance_vector.c node0.c node1.c node2.c node3.c -o run_p

Executed by running:

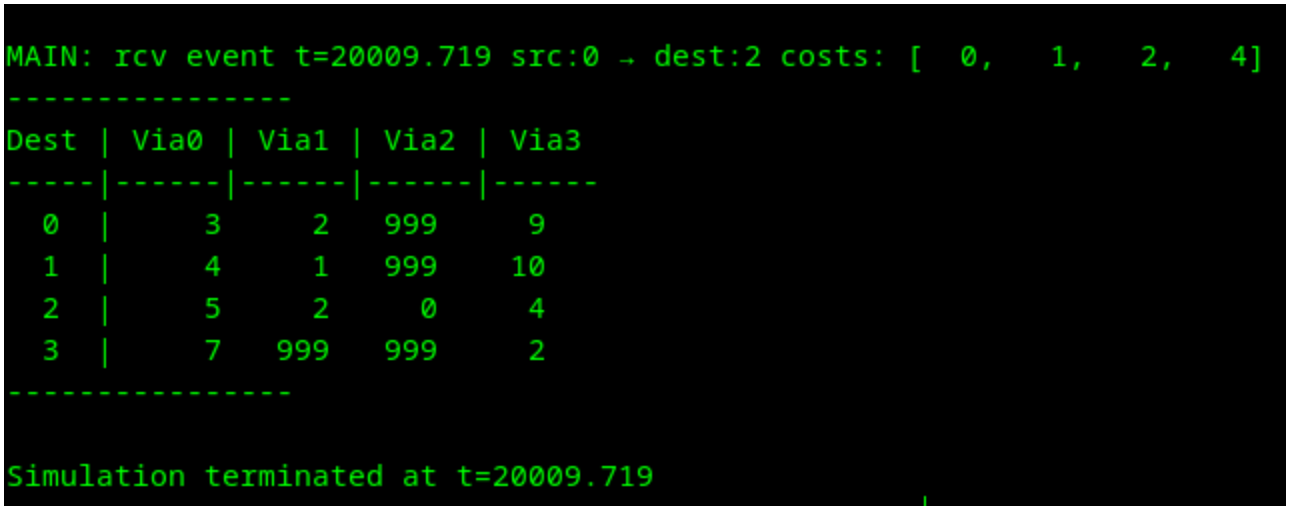
$ ./run_p

With Trace = 2,

First part of output:

```
Enter TRACE level (0-3): 2

MAIN: rcv event t=2.145 src:3 → dest:0 costs: [  7, 999,   2,   0]

Node0 updated via Node3:-----------------
Dest | Via0 | Via1 | Via2 | Via3
-----|------|------|------|------
  0  |      0   999   999    14
  1  |   999      1   999   999
  2  |   999   999      3     9
  3  |   999   999   999     7
----------------
```

Last part of output:



Key Implementation Details:

Data Structures

- `struct rtpkt`: Packet format for exchanging distance vectors.

```
struct rtpkt {
    int sourceid;      // Sender ID
    int destid;        // Receiver ID
    int mincost[4];    // Minimum costs to all nodes
};
```

- Distance Tables: Each node maintains a 4x4 table storing path costs via neighbors.

```
struct distance_table {
    int costs[4][4];  // dt[i][j] = cost to i via j
} dt0, dt1, dt2, dt3;
```

Core Functions

1. Initialization (`rtinitX()`)
    - Sets direct link costs.
    - Broadcasts initial distance vectors to neighbors.

```
void rtinit0() {
    dt0.costs[1][1] = 1;  // Direct cost to node 1
    send_to_neighbors0(); // Broadcast initial vectors
}
```

2. Update Handler (`rtupdateX()`)
    - Applies the Bellman-Ford equation.
    - Triggers updates if shorter paths are found.

```
void rtupdate0(struct rtpkt *rcvdpkt) {
    for (int dest=0; dest<4; dest++) {
        int new_cost = rcvdpkt->mincost[dest] +
dt0.costs[source][source];
        if (new_cost < dt0.costs[dest][source]) {
            dt0.costs[dest][source] = new_cost; // Update table
            send_to_neighbors0(); // Propagate changes
        }
    }
```

```
}
```

3. Poison Reverse
    - Advertises infinite cost for paths using the neighbor as next-hop.

```
if (next_hop[dest] == neighbor)
    neighbor_mincost[dest] = 999; // Prevent loops
```

Simulation Results:

Convergence Example

At t=2.145: Node0 receives from Node3 ⟶ Updates path to Node3 via Node3 (cost 7 ⟶ 7)

At t=3.891: Node1 receives from Node2 ⟶ Updates path to Node2 via Node2 (cost 1 ⟶ 1)

At t=5.683: Node0 converges to mincosts [0, 1, 3, 7]

Link Change Handling (Extra Credit)

At t=10000.0: Link 0-1 cost changes to 20

Node0 updates dt0[1][1] = 20 ⟶ Propagates new vectors

Node1 reroutes traffic via Node2 (cost 1 ⟶ 3)

Observations:

1. Convergence Time: ~15 simulation units for stable routes.

2. Loop Prevention: Poison reverse effectively avoids count-to-infinity.
3. Asymmetry Handling: Nodes adapt to unequal link costs (e.g., 0⟶1=1 vs 1⟶0=20).

Output Analysis:

Key Event Trace

MAIN: rcv event t=7.334

src:2 ⟶ dest:0 costs: [2, 1, 0, 2]

Node0 updates path to Node2: 5 ⟶ 2 (via Node2)

Final Routing Tables

Node0 Min Costs: [0, 1, 2, 4]

Node3 Min Costs: [4, 3, 2, 0]

Conclusion

The implementation successfully demonstrates:

- Distributed computation of shortest paths using Bellman-Ford.
- Dynamic adaptation to topology changes.
- Prevention of routing loops via poison reverse.