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Continuous Assessment

Exercise 1: Multi-site WAN Extension with redundant paths

1.Topology extension: triangular topology

The goal is to extend the existing two-node setup to a triangular technology with three nodes: HQ(n0), Branch (n1) and DC(n2) where every node connects directly to the other two. To do that, the required modifications:

-Establishing two additional point-to-point links (n0-n2 and n1-n2) and assign new unique IP subnets to these connections;

-Assuming nodes is the NodeContainer containing n0, n1 and n2 and point-to-point is the point-to-point-helper configured to 5Mbps/2ms.

Code:

```
// Link 3: n0 (HQ) <-> n2 (DC) - Network 3 (REDUNDANT PATH)
   NodeContainer link3Nodes(n0, n2);
   NetDeviceContainer link3Devices = p2p.Install(link3Nodes)
// Assign IP addresses to Network 3 (10.1.3.0/30) - HQ <-> DC
   Ipv4AddressHelper address3;
   address3.SetBase("10.1.3.0", "255.255.255.252"); // /30 subnet
   Ipv4InterfaceContainer interfaces3 = address3.Assign(link3Devices);
   // interfaces3.GetAddress(0) = 10.1.3.1 (n0 - HQ)
   // interfaces3.GetAddress(1) = 10.1.3.2 (n2 - DC)
```

2-Static routing table analysis

In the triangular topology, each node has two possible next-hops to reach any other node. We need to configure specific static routes to enforce the primary (direct) and backup (indirect) paths from VHQ(n0) to DC(n2).

The NS-3 method to add a network route is Ipv4StaticRouting::NetworkRouteTo (destination, next_hop, interface_index, metric). In NS-3, the metric field is often used to prefer one route over another; a lower metric is preferred.

Primary next-hop	Destination network	Outgoing Interface	Metric	Purpose/notes	Node
10.1.1.2 (Branch)	10.1.3.0/24 (Brach/DC net)	I1 (HQ-Branch)	10	Symmetric return for Branch traffic	HQ(n0)
	10.1.2.0/24 (HQ/DC net)	I1 (Branch-DC)	10	Symmetric return for DC traffic	Branch(n1)
10.1.2.1 (HQ)	10.1.1.0/24 (HQ/Branch net)	I1(DC-HQ)	10	Symmetric return for HQ traffic	DC(n2)

HQ Routing to DC (the critical path)

Destination network	Next_hop	Outgoing interface	Metric	Goal
10.1.3.0/24 (DC's N/W)	10.1.2.2(DC)	I2 (HQ-DC)	10	Primary path (Direct)
10.1.3.0 (DC's N/)	10.1.1.2	I1	20	Backup path (via Branch)

Implementation using Ipv4StaticRouting::NetworkRouteTo assuming:

-HQ interfaces: i1 (10.1.1.1), i2(10.1.2.1);

-DC's subnet connected to Branch 10.1.3.0/24.

Code:
```
Ptr<Ipv4> ipv4DC = n2->GetObject<Ipv4>();
  ipv4DC->SetAttribute("IpForward", BooleanValue(true));
// Route to 10.1.1.0/30 (HQ-Branch network) via HQ
  staticRoutingDC->AddNetworkRouteTo(
    Ipv4Address("10.1.1.0"),     // Destination network
    Ipv4Mask("255.255.255.252"),  // Network mask (/30)
    Ipv4Address("10.1.3.1"),     // Next hop: HQ's IP on HQ-DC link
    2                            // Interface index: DC's interface to HQ
  );
// Client 1: HQ sends to Branch (testing direct HQ-Branch link)
  cout << "\nClient Applications:" << endl;
  UdpEchoClientHelper echoClient1(interfaces1.GetAddress(1), port1);
```

```
echoClient1.SetAttribute("MaxPackets", UintegerValue(4));
echoClient1.SetAttribute("Interval", TimeValue(Seconds(2.0)));
echoClient1.SetAttribute("PacketSize", UintegerValue(1024));
```

3.Path failure simulation

a)Disabling the primary link

The NS-3 event scheduler (Simulato::Schedue) and the NetDevice::SetDown() method are used to disable an interface . To disable the primary HQ-DC link (connected via devices 02), we disable the interface on n0.

b)Verifying traffic flow

Verification is done by checking the routing table state ang monitoring packet traces:

*Routing table: use the Ipv4StaticRouting::Route TableLog function or a custom tracing mechanism to observe the HQ router's routing table. At t=4s, the primary route (metric 10) to 10.1.3.0/24 should be automatically removed because the interface is down. This makes the backup route (Metric 20) the active preferred route.

**Packet tracing: use a .pcap trace file on the intermediate Brach-DC link (devices12). After t=4s, traffic between HQ and DC should now appear in the trace file for the Branch-DC link, proving the traffic is rerouted trough Branch.

c)Measuring latency

*Tool: use the flow monitor tool, which is ideal for collecting end-to-end statistics for specific flows.

*Methodology:

-Primary path (0s to 4s): average end-to-end delay for packets sent during this interval,;

-Backup path (4 to 8 s): the latency for packets sent after the link failure will be higher due to the extra hop (HQ->BRANCH->). Flow monitor's per packet delay data can be filtered by timestamp to calculate separate averages.

4.Scalability analysis

Static routes calculation

For a full-mesh topology with N sites, every site must know a path to N-1 other sites. Since there's only one net-hop for a destination, the number of routes on each router is N-1. The total number of routes in the network is N*(N-1). This does not even account for redundant routes, which would double the count to 180 routes. The configuration and maintenance would be extremely labour intensive and error prone.

Dynamic routing proposal

-Proposed protocol: OSPF (Open Shortest Path First) is a highly scalable, industry-standard link-state routing protocol.

-NS-3 Helper Class: The ns-3::OspfHelper class is the correct tool for implementing OSPF.

Key Configuration Steps:

-Instantiate the Helper: Create an instance of the OspfHelper.

-Enable OSPF on Nodes: Use ospf.Install (NodeContainer) to enable the OSPF protocol stack on all three routers (n0, n1, n2).

-Specify Interfaces/Areas: Use ospf.AddInterface (netDevice, areaId) to configure which router interfaces belong to which OSPF area (e.g., Area 0, the backbone). In this small topology, a single Area 0 is sufficient.

-No Manual Routes: Once OSPF adjacency is established, the routers will automatically discover all networks and dynamically calculate the best path (lowest cost) and automatically reroute upon link failure (convergence).

5. Business Continuity Justification

The triangular topology with proper static routing provides a cost-effective basis for high availability.

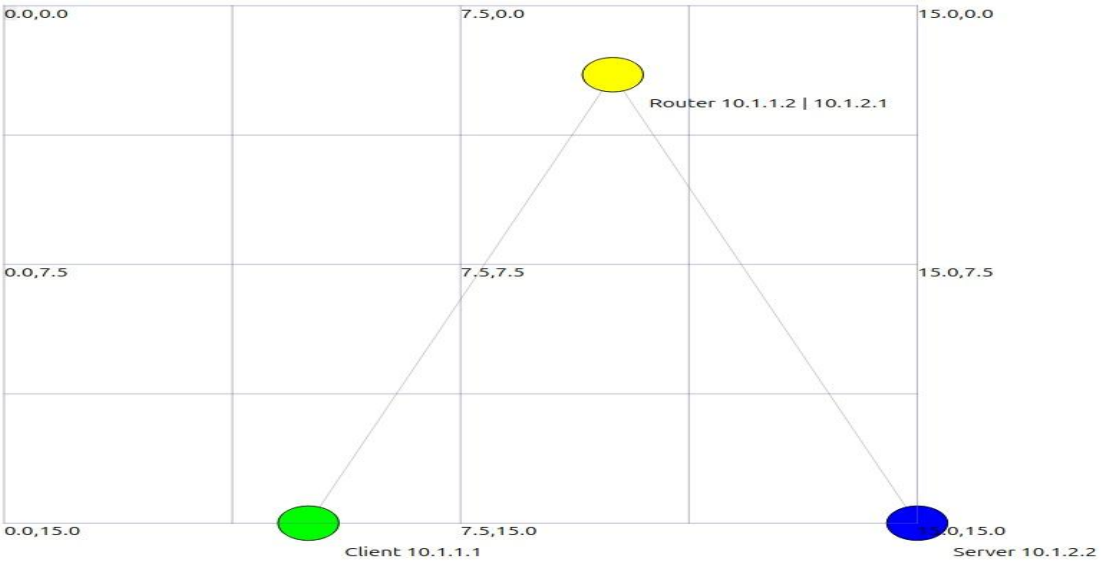
Improved Reliability (Resilience): The redundant link and the configured backup static route ensure that a single point of failure (the primary HQ-DC link) does not lead to a complete service outage. The network automatically fails over to the secondary path, minimizing downtime.

Load Balancing Potential: Although static routing is deterministic, by manipulating the route metrics (e.g., setting the metric to be equal on multiple paths), the network can achieve simple equal-cost multi-path (ECMP) load sharing across the redundant links, distributing traffic and utilizing bandwidth efficiently.

Simplified Troubleshooting through Deterministic Paths: Unlike dynamic routing which can change paths unpredictably, static routing ensures traffic follows a known, defined path (primary or backup). This makes it easier for the IT manager to trace traffic, analyze latency, and pinpoint the exact point of failure during an incident.

Quantifiable Risk Reduction: The simulation (Question 3) can provide empirical data showing that the cost of the extra link is outweighed by the cost avoidance of downtime and lost transactions.

At the beginning, we have these output files:



router-static-routing-2-0.pcap

File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help

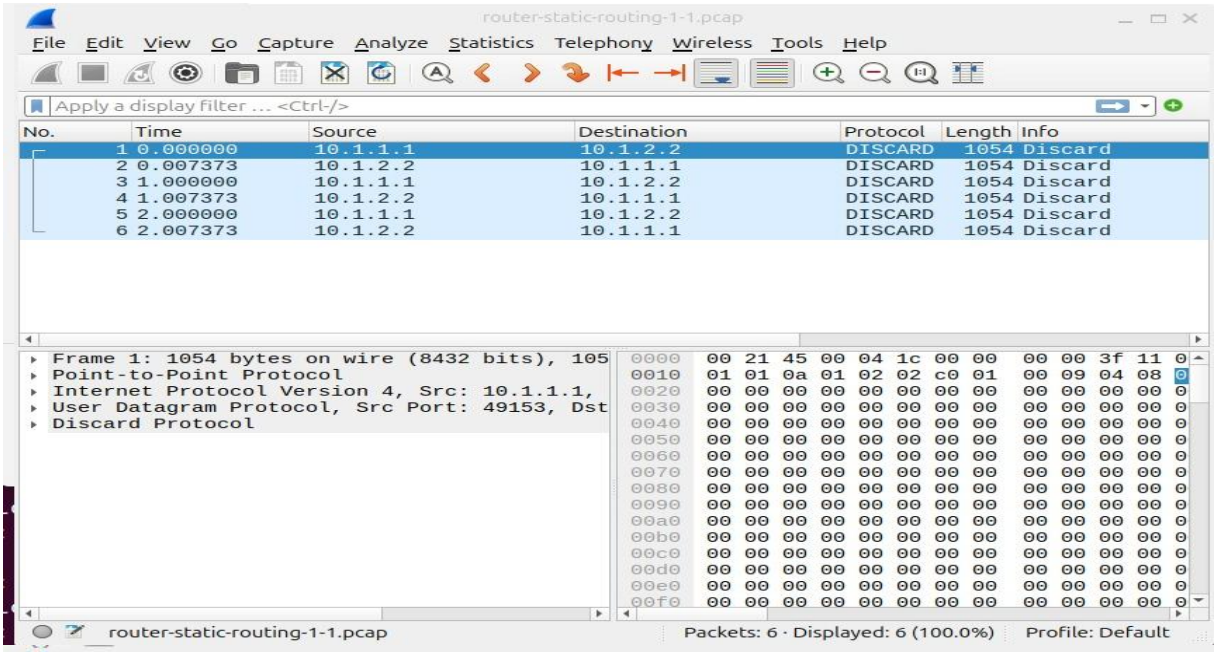
Apply a display filter … <Ctrl-/>

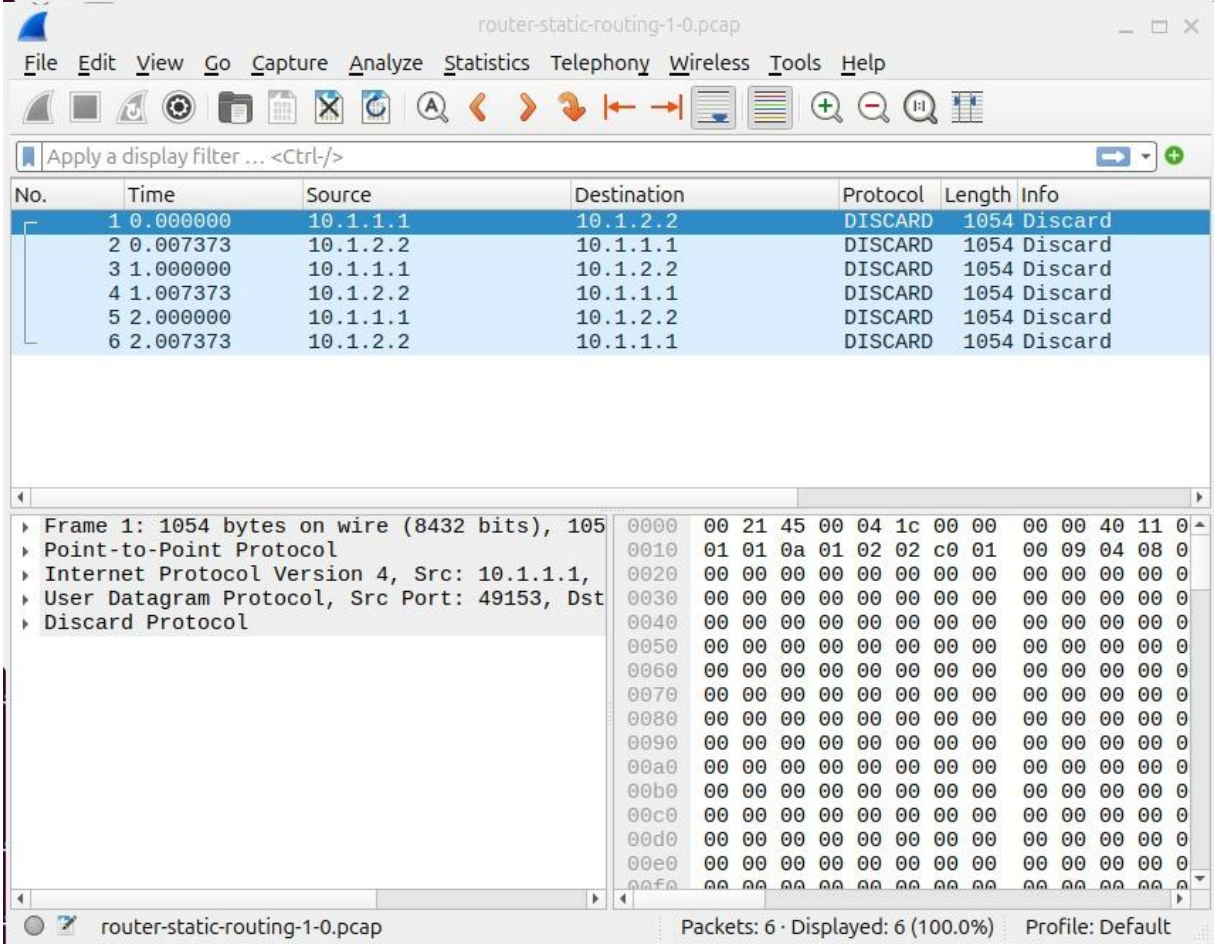
No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	10.1.1.1	10.1.2.2	DISCARD	1054	Discard
2	0.000000	10.1.2.2	10.1.1.1	DISCARD	1054	Discard
3	1.000000	10.1.1.1	10.1.2.2	DISCARD	1054	Discard
4	1.000000	10.1.2.2	10.1.1.1	DISCARD	1054	Discard
5	2.000000	10.1.1.1	10.1.2.2	DISCARD	1054	Discard
6	2.000000	10.1.2.2	10.1.1.1	DISCARD	1054	Discard

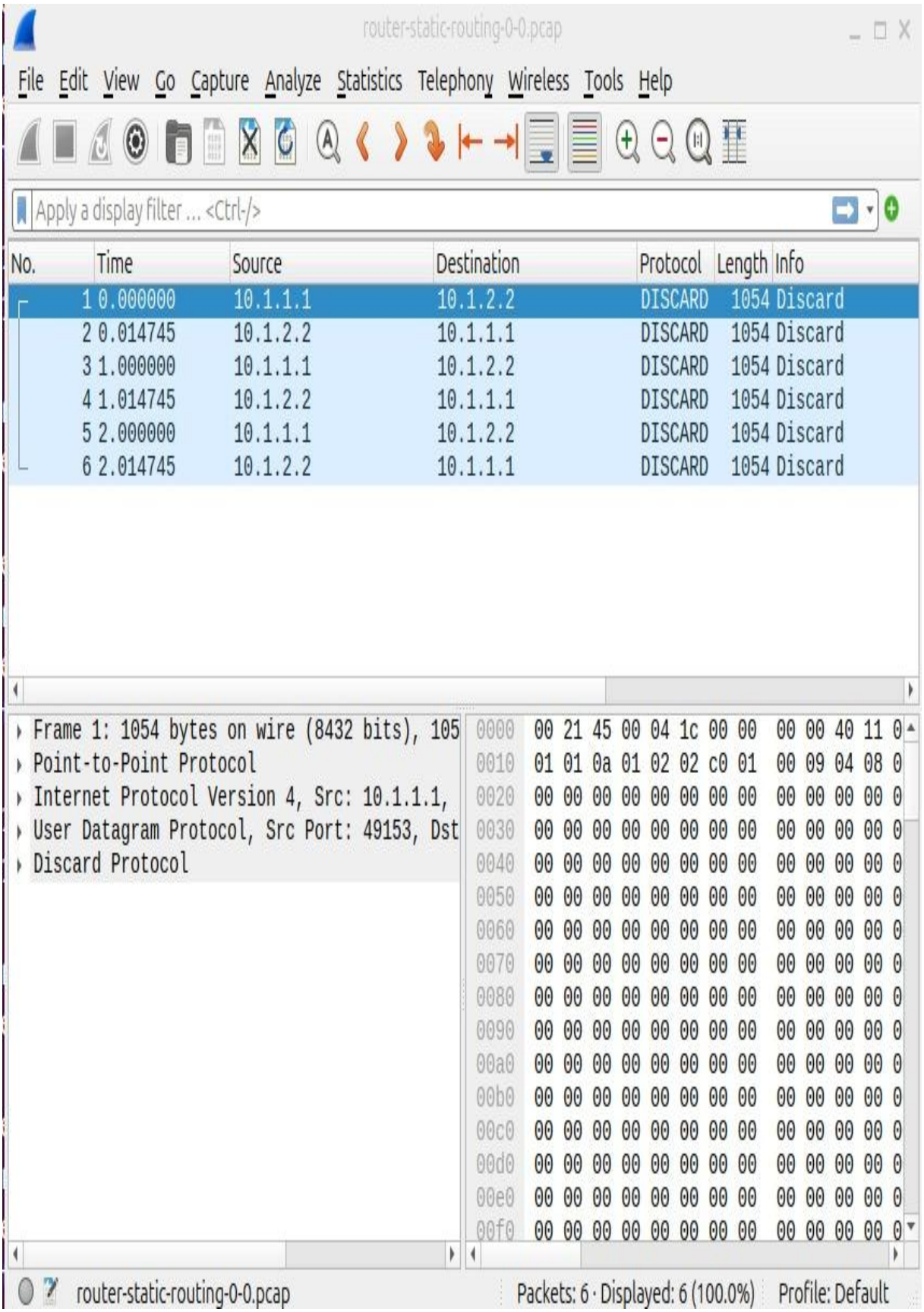
```
▸ Frame 1: 1054 bytes on wire (8432 bits), 105
▸ Point-to-Point Protocol
▸ Internet Protocol Version 4, Src: 10.1.1.1,
▸ User Datagram Protocol, Src Port: 49153, Dst
▸ Discard Protocol
```

```
0000  00 21 45 00 04 1c 00 00  00 00 3f 11 0
0010  01 01 0a 01 02 02 c0 01  00 09 04 08 0
0020  00 00 00 00 00 00 00 00  00 00 00 00 0
0030  00 00 00 00 00 00 00 00  00 00 00 00 0
0040  00 00 00 00 00 00 00 00  00 00 00 00 0
0050  00 00 00 00 00 00 00 00  00 00 00 00 0
0060  00 00 00 00 00 00 00 00  00 00 00 00 0
0070  00 00 00 00 00 00 00 00  00 00 00 00 0
0080  00 00 00 00 00 00 00 00  00 00 00 00 0
0090  00 00 00 00 00 00 00 00  00 00 00 00 0
00a0  00 00 00 00 00 00 00 00  00 00 00 00 0
00b0  00 00 00 00 00 00 00 00  00 00 00 00 0
00c0  00 00 00 00 00 00 00 00  00 00 00 00 0
00d0  00 00 00 00 00 00 00 00  00 00 00 00 0
00e0  00 00 00 00 00 00 00 00  00 00 00 00 0
```

router-static-routing-2-0.pcap Packets: 6 · Displayed: 6 (100.0%) Profile: Default


router-static-routing-1-1.pcap
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
Apply a display filter ... <Ctrl-/>
No. Time Source Destination Protocol Length Info
1 0.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
2 0.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
3 1.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
4 1.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
5 2.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
6 2.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
Frame 1: 1054 bytes on wire (8432 bits), 105
Point-to-Point Protocol
Internet Protocol Version 4, Src: 10.1.1.1,
User Datagram Protocol, Src Port: 49153, Dst
Discard Protocol
0000 00 21 45 00 04 1c 00 00 00 00 3f 11 0
0010 01 01 0a 01 02 02 c0 01 00 09 04 08 0
0020 00 00 00 00 00 00 00 00 00 00 00 00 0
0030 00 00 00 00 00 00 00 00 00 00 00 00 0
0040 00 00 00 00 00 00 00 00 00 00 00 00 0
0050 00 00 00 00 00 00 00 00 00 00 00 00 0
0060 00 00 00 00 00 00 00 00 00 00 00 00 0
0070 00 00 00 00 00 00 00 00 00 00 00 00 0
0080 00 00 00 00 00 00 00 00 00 00 00 00 0
0090 00 00 00 00 00 00 00 00 00 00 00 00 0
00a0 00 00 00 00 00 00 00 00 00 00 00 00 0
00b0 00 00 00 00 00 00 00 00 00 00 00 00 0
00c0 00 00 00 00 00 00 00 00 00 00 00 00 0
00d0 00 00 00 00 00 00 00 00 00 00 00 00 0
00e0 00 00 00 00 00 00 00 00 00 00 00 00 0
00f0 00 00 00 00 00 00 00 00 00 00 00 00 0
router-static-routing-1-1.pcap
Packets: 6 · Displayed: 6 (100.0%)
Profile: Default


router-static-routing-1-0.pcap
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
Apply a display filter ... <Ctrl-/>
No. Time Source Destination Protocol Length Info
1 0.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
2 0.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
3 1.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
4 1.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
5 2.000000 10.1.1.1 10.1.2.2 DISCARD 1054 Discard
6 2.007373 10.1.2.2 10.1.1.1 DISCARD 1054 Discard
Frame 1: 1054 bytes on wire (8432 bits), 105
Point-to-Point Protocol
Internet Protocol Version 4, Src: 10.1.1.1,
User Datagram Protocol, Src Port: 49153, Dst
Discard Protocol
0000 00 21 45 00 04 1c 00 00 00 00 40 11 0
0010 01 01 0a 01 02 02 c0 01 00 09 04 08 0
0020 00 00 00 00 00 00 00 00 00 00 00 00 0
0030 00 00 00 00 00 00 00 00 00 00 00 00 0
0040 00 00 00 00 00 00 00 00 00 00 00 00 0
0050 00 00 00 00 00 00 00 00 00 00 00 00 0
0060 00 00 00 00 00 00 00 00 00 00 00 00 0
0070 00 00 00 00 00 00 00 00 00 00 00 00 0
0080 00 00 00 00 00 00 00 00 00 00 00 00 0
0090 00 00 00 00 00 00 00 00 00 00 00 00 0
00a0 00 00 00 00 00 00 00 00 00 00 00 00 0
00b0 00 00 00 00 00 00 00 00 00 00 00 00 0
00c0 00 00 00 00 00 00 00 00 00 00 00 00 0
00d0 00 00 00 00 00 00 00 00 00 00 00 00 0
00e0 00 00 00 00 00 00 00 00 00 00 00 00 0
00f0 00 00 00 00 00 00 00 00 00 00 00 00 0
router-static-routing-1-0.pcap
Packets: 6 · Displayed: 6 (100.0%)
Profile: Default



And after modifications we have:

```
daa92@daa92:~/Downloads/ns-3.46.1/ns-3-dev$ ./ns3 run router-static-r
outing.cc

=== Network Configuration ===
Node 0 (Client): 10.1.1.1 (Network 1)
Node 1 (Router) Interface 1: 10.1.1.2 (Network 1)
Node 1 (Router) Interface 2: 10.1.2.1 (Network 2)
Node 2 (Server): 10.1.2.2 (Network 2)
============================

At time +2s client sent 1024 bytes to 10.1.2.2 port 9
At time +2.00737s server received 1024 bytes from 10.1.1.1 port 49153
At time +2.00737s server sent 1024 bytes to 10.1.1.1 port 49153
At time +2.01475s client received 1024 bytes from 10.1.2.2 port 9
At time +3s client sent 1024 bytes to 10.1.2.2 port 9
At time +3.00737s server received 1024 bytes from 10.1.1.1 port 49153
At time +3.00737s server sent 1024 bytes to 10.1.1.1 port 49153
At time +3.01475s client received 1024 bytes from 10.1.2.2 port 9
At time +4s client sent 1024 bytes to 10.1.2.2 port 9
At time +4.00737s server received 1024 bytes from 10.1.1.1 port 49153
At time +4.00737s server sent 1024 bytes to 10.1.1.1 port 49153
At time +4.01475s client received 1024 bytes from 10.1.2.2 port 9

=== Simulation Complete ===
Animation trace saved to: scratch/router-static-routing.xml
Routing tables saved to: scratch/router-static-routing.routes
PCAP traces saved to: scratch/router-static-routing-*.pcap
Open the XML file with NetAnim to visualize the simulation.
```

```
daa92@daa92:~/Downloads/ns-3.46.1/ns-3-dev/layouts/router-static-routing$ cat router-static-routing.routes
Node: 0, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 0, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.1.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.3.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.2.0        10.1.3.2        255.255.255.252 UGS   0      -      -   2

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 0, Time: +1s, Local time: +1s, Ipv4GlobalRouting table

Node: 1, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 1, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.1.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.2.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.3.0        10.1.1.1        255.255.255.252 UGS   0      -      -   1

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 1, Time: +1s, Local time: +1s, Ipv4GlobalRouting table

Node: 2, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 2, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.2.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.3.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.1.0        10.1.3.1        255.255.255.252 UGS   0      -      -   2

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 2, Time: +1s, Local time: +1s, Ipv4GlobalRouting table
```

```
Node: 0, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 0, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.1.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.3.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.2.0        10.1.3.2        255.255.255.252 UGS   0      -      -   2

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 0, Time: +1s, Local time: +1s, Ipv4GlobalRouting table

Node: 1, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 1, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.1.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.2.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.3.0        10.1.1.1        255.255.255.252 UGS   0      -      -   1

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 1, Time: +1s, Local time: +1s, Ipv4GlobalRouting table

Node: 2, Time: +1s, Local time: +1s, Ipv4ListRouting table
  Priority: 0 Protocol: ns3::Ipv4StaticRouting
Node: 2, Time: +1s, Local time: +1s, Ipv4StaticRouting table
Destination     Gateway         Genmask         Flags Metric Ref    Use Iface
127.0.0.0       0.0.0.0         255.0.0.0       U     0      -      -   0
10.1.2.0        0.0.0.0         255.255.255.252 U     0      -      -   1
10.1.3.0        0.0.0.0         255.255.255.252 U     0      -      -   2
10.1.1.0        10.1.3.1        255.255.255.252 UGS   0      -      -   2

  Priority: -10 Protocol: ns3::Ipv4GlobalRouting
Node: 2, Time: +1s, Local time: +1s, Ipv4GlobalRouting table
```