Exercise 1: Multi-Site WAN Extension with Redundant Paths

Introduction

This exercise extends the baseline NS-3 static routing simulation from a simple two-network topology to a triangular multi-site WAN with redundant connectivity. The original topology connects two networks through a single router, while the enhanced topology creates a resilient mesh between three sites: Headquarters (HQ), Branch Office, and Data Center (DC).

Question 1: Topology Extension

Network Architecture

The triangular topology requires creating three additional point-to-point links beyond the original two links. The complete topology is:

Original Links:

- Link 1: n0 (HQ) ↔ n1 (Branch) - Network 1 (10.1.1.0/24)
- Link 2: n1 (Branch) ↔ n2 (DC) - Network 2 (10.1.2.0/24)

New Links to Add:

- Link 3: n0 (HQ) ↔ n2 (DC) - Network 3 (10.1.3.0/24)

C++ Code Modifications

Step 1: Create the third point-to-point link

Insert this code after the existing link2Devices creation:

```
cpp
```

```
// Link 3: n0 <-> n2 (Network 3) - Direct HQ to DC connection
NodeContainer link3Nodes(n0, n2);
NetDeviceContainer link3Devices = p2p.Install(link3Nodes);
```

Step 2: Assign IP addresses to Network 3

Insert this code after the address2.Assign() call:

cpp

```
// Assign IP addresses to Network 3 (10.1.3.0/24)
Ipv4AddressHelper address3;
address3.SetBase("10.1.3.0", "255.255.255.0");
Ipv4InterfaceContainer interfaces3 = address3.Assign(link3Devices);
// interfaces3.GetAddress(0) = 10.1.3.1 (n0's interface on Network 3)
// interfaces3.GetAddress(1) = 10.1.3.2 (n2's interface on Network 3)
```

Step 3: Enable IP forwarding on all nodes

Since all nodes now act as routers, modify the IP forwarding configuration:

cpp

```
// Enable IP forwarding on all nodes (they all route now)
Ptr<Ipv4> ipv4N0 = n0->GetObject<Ipv4>();
ipv4N0->SetAttribute("IpForward", BooleanValue(true));

Ptr<Ipv4> ipv4N1 = n1->GetObject<Ipv4>();
ipv4N1->SetAttribute("IpForward", BooleanValue(true));

Ptr<Ipv4> ipv4N2 = n2->GetObject<Ipv4>();
ipv4N2->SetAttribute("IpForward", BooleanValue(true));
```

Complete IP Address Assignment

Node	Interface	Network	IP Address	Purpose
n0 (HQ)	eth0	Network 1	10.1.1.1	To Branch
n0 (HQ)	eth1	Network 3	10.1.3.1	To DC (direct)
n1 (Branch)	eth0	Network 1	10.1.1.2	To HQ
n1 (Branch)	eth1	Network 2	10.1.2.1	To DC
n2 (DC)	eth0	Network 2	10.1.2.2	To Branch

Node	Interface	Network	IP Address	Purpose
n2 (DC)	eth1	Network 3	10.1.3.2	To HQ (direct)

Question 2: Static Routing Table Analysis

Routing Strategy

Primary Path Requirements:

- HQ → DC: Direct path via Network 3 (10.1.3.0/24)
- Backup Path: HQ → Branch → DC via Networks 1 and 2

Route Metrics:

- Primary routes: Lower metric (e.g., metric = 1)
- Backup routes: Higher metric (e.g., metric = 10)

Complete Static Routing Tables

Node n0 (HQ) Routing Configuration

```cpp
```

```
Ptr<Ipv4StaticRouting> staticRoutingN0 =
    staticRoutingHelper.GetStaticRouting(n0->GetObject<Ipv4>());

// Primary route to DC's network (10.1.2.0/24) via direct link
staticRoutingN0->AddNetworkRouteTo(
    Ipv4Address("10.1.2.0"),      // DC's Branch-side network
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.3.2"),      // Next hop: DC via Network 3
    2,                            // Interface 2 (Network 3)
    1                             // Metric (primary)
);

// Backup route to DC via Branch
staticRoutingN0->AddNetworkRouteTo(
    Ipv4Address("10.1.2.0"),      // DC's Branch-side network
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.1.2"),      // Next hop: Branch
    1,                            // Interface 1 (Network 1)
    10                             // Metric (backup)
);

// Route to DC's direct network (already connected via Network 3)
// No explicit route needed - directly connected
```

Routing Table for n0:

Destination Network	Netmask	Next Hop	Interface	Metric	Type
10.1.1.0	255.255.255.0	-	eth0	0	Direct
10.1.3.0	255.255.255.0	-	eth1	0	Direct
10.1.2.0	255.255.255.0	10.1.3.2	eth1	1	Primary
10.1.2.0	255.255.255.0	10.1.1.2	eth0	10	Backup

Node n1 (Branch) Routing Configuration

cpp

```
Ptr<Ipv4StaticRouting> staticRoutingN1 =
    staticRoutingHelper.GetStaticRouting(n1->GetObject<Ipv4>());

// Route to HQ-DC direct network (10.1.3.0/24)
// Via HQ
staticRoutingN1->AddNetworkRouteTo(
    Ipv4Address("10.1.3.0"),
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.1.1"),      // Next hop: HQ
    1,                            // Interface 1 (Network 1)
    1
);

// Via DC
staticRoutingN1->AddNetworkRouteTo(
    Ipv4Address("10.1.3.0"),
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.2.2"),      // Next hop: DC
    2,                            // Interface 2 (Network 2)
    1
);
```

Routing Table for n1:

Destination Network	Netmask	Next Hop	Interface	Metric	Type
10.1.1.0	255.255.255.0	-	eth0	0	Direct
10.1.2.0	255.255.255.0	-	eth1	0	Direct
10.1.3.0	255.255.255.0	10.1.1.1	eth0	1	Via HQ
10.1.3.0	255.255.255.0	10.1.2.2	eth1	1	Via DC

Node n2 (DC) Routing Configuration

cpp

```
Ptr<Ipv4StaticRouting> staticRoutingN2 =
    staticRoutingHelper.GetStaticRouting(n2->GetObject<Ipv4>());

// Primary route to HQ's network (10.1.1.0/24) via direct link
staticRoutingN2->AddNetworkRouteTo(
    Ipv4Address("10.1.1.0"),
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.3.1"),      // Next hop: HQ via Network 3
    2,                            // Interface 2 (Network 3)
    1                             // Metric (primary)
);

// Backup route to HQ via Branch
staticRoutingN2->AddNetworkRouteTo(
    Ipv4Address("10.1.1.0"),
    Ipv4Mask("255.255.255.0"),
    Ipv4Address("10.1.2.1"),      // Next hop: Branch
    1,                            // Interface 1 (Network 2)
    10                             // Metric (backup)
);
```

Routing Table for n2:

Destination Network	Netmask	Next Hop	Interface	Metric	Type
10.1.2.0	255.255.255.0	-	eth0	0	Direct
10.1.3.0	255.255.255.0	-	eth1	0	Direct
10.1.1.0	255.255.255.0	10.1.3.1	eth1	1	Primary
10.1.1.0	255.255.255.0	10.1.2.1	eth0	10	Backup

Symmetric Routing Explanation

Symmetric routing ensures that the return path matches the forward path. In this configuration:

- When HQ sends to DC via direct link (10.1.3.x), DC responds via the same direct link
- The metric-based routing ensures both directions prefer the primary path
- Return traffic uses the same interface through which the request arrived

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Question 3: Path Failure Simulation

A) Disabling the Primary HQ-DC Link at t=4 seconds

```cpp
// Schedule link failure at t=4 seconds
Simulator::Schedule(Seconds(4.0), &NetDevice::SetDown,
                    link3Devices.Get(0));  // Disable n0's interface
Simulator::Schedule(Seconds(4.0), &NetDevice::SetDown,
                    link3Devices.Get(1));  // Disable n2's interface

std::cout << "Link failure scheduled at t=4.0s (HQ-DC direct link)\n";
```

Alternative method using Channel:

```cpp
// Disable the channel connecting HQ and DC
Ptr<PointToPointChannel> channel3 =
   link3Devices.Get(0)->GetChannel()->GetObject<PointToPointChannel>();

Simulator::Schedule(Seconds(4.0), &PointToPointChannel::SetAttribute,
                    channel3, "Delay", TimeValue(Seconds(999999)));
```

B) Verifying Backup Path Traffic Flow

Method 1: Using Trace Sources

```cpp
```

```
// Enable ASCII tracing to monitor packet paths
AsciiTraceHelper ascii;
p2p.EnableAsciiAll(ascii.CreateFileStream("router-failover.tr"));

// Add custom packet trace on Branch router to detect rerouted traffic
void PacketSinkTrace(Ptr<const Packet> packet)
{
   std::cout << "Packet transiting through Branch at "
             << Simulator::Now().GetSeconds() << "s\n";
}

// Connect trace after simulation start
Ptr<NetDevice> branchDevice = link1Devices.Get(1);  // n1's device
branchDevice->TraceConnectWithoutContext("PhyRxEnd",
                                         MakeCallback(&PacketSinkTrace));
```

Method 2: Traffic Observation

Before failure ($t < 4s$): Packets visible on link3 PCAP traces
After failure ($t \geq 4s$): Packets visible on link1 and link2 PCAP traces

C) Latency Measurement Using FlowMonitor

cpp

```
// Install FlowMonitor
FlowMonitorHelper flowHelper;
Ptr<FlowMonitor> monitor = flowHelper.InstallAll();

// At end of simulation, analyze flows
monitor->CheckForLostPackets();
Ptr<Ipv4FlowClassifier> classifier =
  DynamicCast<Ipv4FlowClassifier>(flowHelper.GetClassifier());

FlowMonitor::FlowStatsContainer stats = monitor->GetFlowStats();

for (auto it = stats.begin(); it != stats.end(); ++it)
{
  Ipv4FlowClassifier::FiveTuple tuple = classifier->FindFlow(it->first);

  double avgDelay = it->second.delaySum.GetSeconds() /
                    it->second.rxPackets;

  std::cout << "Flow " << it->first << " ("
            << tuple.sourceAddress << " -> "
            << tuple.destinationAddress << ")\n";
  std::cout << "  Average Delay: " << avgDelay * 1000 << " ms\n";
  std::cout << "  Packets Sent: " << it->second.txPackets << "\n";
  std::cout << "  Packets Received: " << it->second.rxPackets << "\n";
}
```

Expected Results:

Time Period	Path	Expected Delay
t = 0-4s	Direct (HQ→DC)	~2ms (single hop)
t = 4-11s	Via Branch (HQ→Branch→DC)	~4ms (two hops)

Question 4: Scalability Analysis

Static Route Calculation for Full Mesh

For **N sites** in a full mesh topology:

- Each site needs routes to (N-1) other sites
- Total static routes = **N × (N-1)**

For 10 sites:

- Routes per site: 9
- Total routes across network: **10 × 9 = 90 routes**

Administrative Overhead

Sites	Routes per Site	Total Routes	Configuration Complexity
3	2	6	Low
5	4	20	Medium
10	9	90	High
20	19	380	Very High
50	49	2,450	Unmanageable

Dynamic Routing Solution: OSPF

NS-3 Implementation using OspfHelper:

```cpp
// Replace static routing with OSPF
#include "ns3/ospf-helper.h"

// Install OSPF instead of configuring static routes
OspfHelper ospf;
ospf.Install(nodes);  // Install on all nodes

// OSPF automatically discovers neighbors and builds routing tables
// No manual route configuration needed
```

Key OSPF Configuration Steps:

1. **Enable OSPF on all router interfaces:**

```cpp
ospf.SetRouterId(n0, Ipv4Address("1.1.1.1"));
ospf.SetRouterId(n1, Ipv4Address("2.2.2.2"));
ospf.SetRouterId(n2, Ipv4Address("3.3.3.3"));
```

2. **Define OSPF areas:**

```cpp
// All interfaces in Area 0 (backbone)
ospf.SetArea(nodes, 0);
```

3. **Set interface costs (optional):**

```cpp
// Primary links: cost 1
// Backup links: cost 10
ospf.SetInterfaceCost(n0, 1, 1);   // Primary
ospf.SetInterfaceCost(n0, 2, 10);  // Backup
```

Benefits over Static Routing:

- **Automatic neighbor discovery** - No manual next-hop configuration
- **Dynamic convergence** - Adapts to link failures automatically (convergence time ~seconds)
- **Load balancing** - Can utilize equal-cost multiple paths (ECMP)
- **Scalability** - O(N) configuration complexity instead of $O(N^2)$

Question 5: Business Continuity Justification

Technical Justification for Triangular Topology with Redundant Links

To: IT Management
From: Network Engineering Team
Re: Investment in Redundant WAN Architecture

The proposed triangular topology with static routing provides critical business continuity advantages:

1. Improved Reliability

- **Zero Single Point of Failure:** Any single link failure maintains connectivity between all sites
- **Quantified Uptime:** With 99.9% per-link reliability, dual paths increase end-to-end availability to 99.9999% (five nines)
- **Business Impact:** Prevents revenue loss during link failures (estimated $50K/hour downtime cost)

2. Load Balancing Potential

- **Traffic Distribution:** Primary and backup paths allow traffic engineering to distribute load
- **Bandwidth Optimization:** During normal operation, backup links can carry non-critical traffic
- **Cost Efficiency:** Maximizes ROI on all installed links rather than leaving backup capacity idle

3. Simplified Troubleshooting Through Deterministic Paths

- **Predictable Routing:** Static routes create explicit, documented traffic flows
- **Faster Issue Resolution:** Network engineers know exactly which path traffic takes under normal/failure conditions
- **Compliance:** Deterministic routing simplifies audit trails and security monitoring
- **Testing:** Can validate backup paths proactively without impacting production traffic

4. Incremental Deployment Path to Dynamic Routing

- The triangular physical topology provides the foundation for future OSPF deployment
- Static routing allows team to learn the topology before introducing protocol complexity
- Investment protects against both current needs and future scalability requirements

Return on Investment: The cost of redundant links (estimated $X/month) is offset by preventing a single 4-hour outage per year.

Conclusion

This exercise demonstrated extending a simple NS-3 linear topology to a resilient triangular WAN with redundant connectivity. Key accomplishments include:

1. Adding a third point-to-point link with proper IP addressing (Network 3: 10.1.3.0/24)
2. Configuring metric-based static routing for primary/backup path selection
3. Implementing and testing link failure scenarios using NS-3's event scheduler
4. Analyzing scalability limitations of static routing ($O(N^2)$ complexity)
5. Proposing OSPF as a dynamic routing solution for larger deployments

The triangular topology provides improved reliability, load balancing opportunities, and deterministic troubleshooting while maintaining manageable complexity for a three-site deployment.

References

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