

Building BT Network

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Lab Report**

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Abstract

In this lab, our team set out to build BT Network, a small version of Tier-2 Internet Service Provider (ISP) located at Haslegrave Building, from scratch.

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Chapter 1

Introduction

In this lab, our team set out to build BT Network, a small version of Tier-2 Internet Service Provider (ISP) located at Haslegrave Building, from scratch. Despite its limitations in terms of size and Internet access, we can proudly attest that BT Network is one of the leading providers at Haslegrave Building.

BT network is a Autonomous System (AS) as a whole and the AS Number is 2030. Its domain name is `bt.lbboro`.

1.1 Network Services

Our network provides the following services to each of our individual customers.

- IP addressing with a guaranteed range of 14 host addresses allocated from `23.0.0.0/8` (IPv4) and `2001:2300::/32` (IPv6) blocks.
- Intra-domain Internet connection with Intermediate System to Intermediate System (IS-IS) routing protocol.
- Inter-domain Internet connection with Border Gateway Protocol (BGP).
- A reliable Domain name System (DNS) service with duplicated servers under domain `bt.lbboro`.
- A World Wide Web (WWW) service located at `http://bt.lbboro/`.
- Email service at `bt.lbboro`.

For neighbouring ISPs who is a customer in our business relationships (see Section 1.2.3), we provide the following services.

- Internet connection to our domain as well as all the others'.

In addition, we provide secure remote access to our routers through Secure Shell (SSH) protocol on one of our laptops for administrative purposes.

1.2 Business Relationships with Neighbouring ISPs

BT Network has three immediate neighbouring ISPs and it's important to form business relationships with all three of them in order to gain economic benefits. The external routing policies of BGP protocol for each outside network are determined by the business relationship with which our network is connected to (see Section 3.2 for details). Our business relationships with neighbouring ISPs are shown in Figure 1.1 and elaborated in the following.

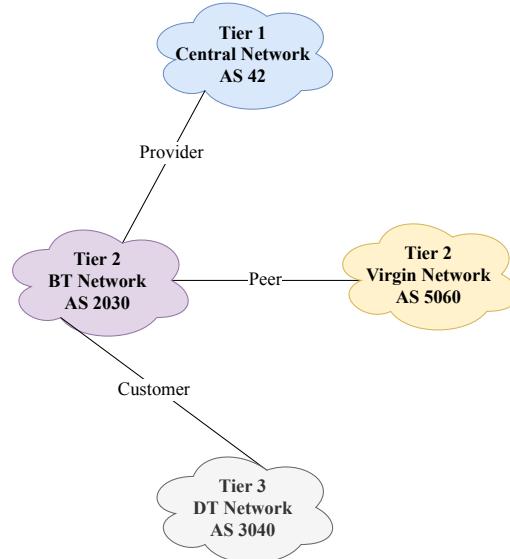


Figure 1.1: Business Relationships of BT Network with Neighbouring ISPs.

1.2.1 Provider: Central Network

Since BT Network is a Tier-2 ISP, it needs to be connected to a Tier-1 ISP to gain wider Internet connection. Therefore, BT is connected to Central Network as a customer, a Tier-1 ISP, which makes Central Network a network provider for BT.

1.2.2 Peer: Virgin Network

BT Network forms a Peer relationship with Virgin Network, which allows Virgin Network to connect to BT Network at zero cost and vice versa.

1.2.3 Customer: DT Network

BT Network forms a Provider-Customer relationship with DT Network, in which BT is the provider and DT is the customer. In other words, DT gains access to the border Internet through BT at a cost.

1.3 Roles of Network Components

There are 6 physical components in our network in total, of which 3 are Cisco routers and the other 3 are TOSHIBA laptops. Each component plays an important role in the network as shown in Figure 1.2.

1.3.1 Routers

In terms of connection, each router is attached with one customer subnet and thus providing Internet service to one customer. Router 1 (BT-R001) is not physically connected to any outside network, while Router 2 (BT-R002) is connected to DT Network and Router 3 (BT-R003) is connected to Virgin Network and Central Network through cables.

In terms of routing, all routers are Level-1 routers in intra-domain IS-IS routing protocol. In BGP routing protocol, Router 1 (BT-R001) acts as an Internal BGP (IBGP) router while Router 2 (BT-R002) and Router 3 (BT-R003) act as External BGP (EBGP) routers.

1.3.2 Laptops

All laptops are running a Ubuntu 16.04 system. Each of them is connected to a customer subnet through a cable. In terms of services, Laptop 1 (BT001) provides DNS service for `bt.1boro` as a secondary DNS server and WWW service at `http://bt.1boro`. It also acts as a secure SSH access point to routers for administrative purposes. Laptop 2 (BT002) doesn't provide any service and thus acts as a normal user in the network. Laptop 3 (BT003) provides a DNS service for `bt.1boro` as a primary DNS server. In addition, it provides an Email service at `bt.1boro`.

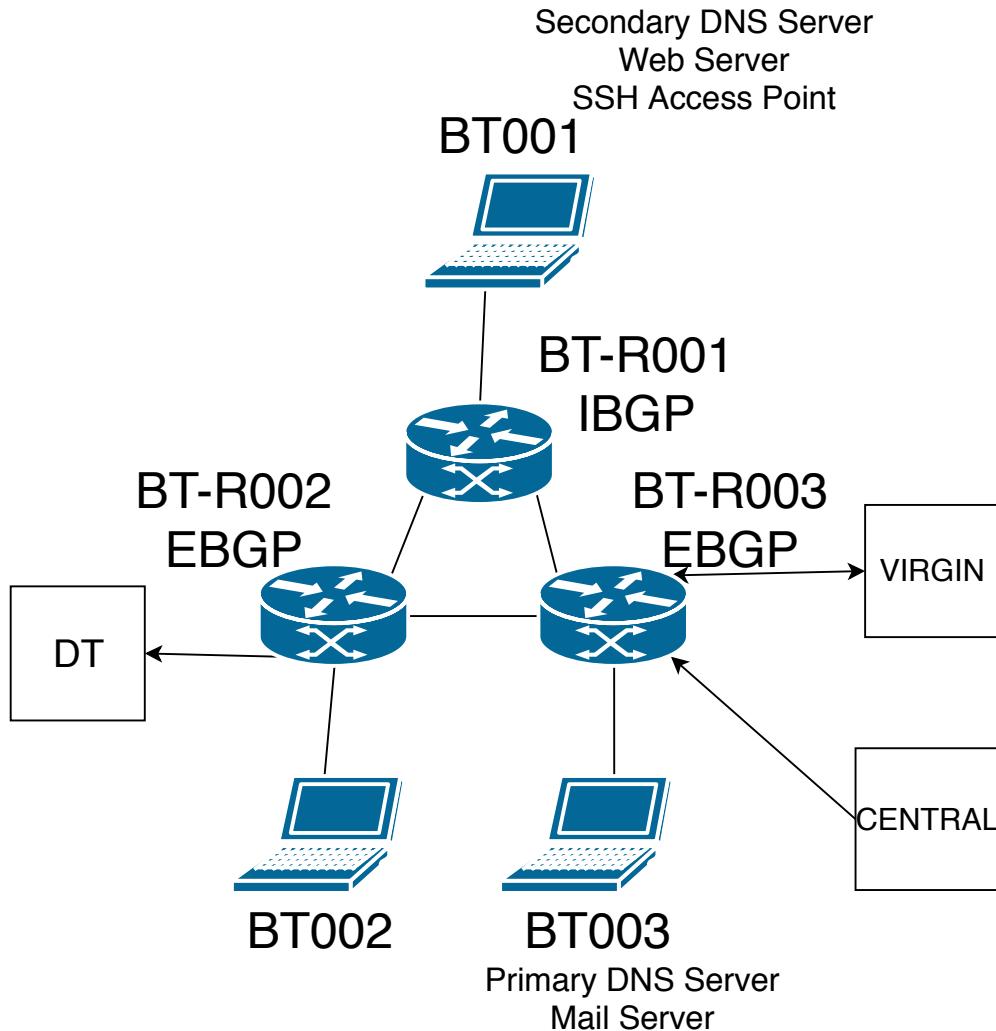


Figure 1.2: Roles of Main Components in BT Network.

1.4 Organisation of the Report

The report is organised as follows. We describe the architecture of BT Network on the network layer in Chapter 2. A Network Diagram involving all physical components and connections is drawn in the chapter. Then, IP addresses for interfaces in the network are carefully allocated and configured.

In order to allow packets to be forwarded within and outside the network, proper intra-domain and inter-domain routing protocols are set up and tested in Chapter 3.

In Chapter 4, we move up to the application layer and set up various services in the

CHAPTER 1. INTRODUCTION

network as listed in Section 1.1.

Main conclusions drawn from the building process and possible further work are discussed in Chapter 5. At last, a summary of contributions for each group member is presented in Chapter 6.

Although the report does not necessarily reflect the actual order of steps in our building process (eg. remote SSH access was set up before BGP), readers can be assured that all results presented can be reproduced by following the natural order of the report.

To ensure readability, rationale behind important decisions made, problems we encountered and their respective solutions, alternative ways of configurations (if any) as well as reflective commentary for each step of implementation are documented in the report.

Chapter 2

Network Architecture

2.1 Network Diagram

2.1.1 Description

A full diagram of BT network is shown in Figure 2.1. There are 3 routers in the network, whose names are BT-R001, BT-R002 and BT-R003 respectively, connected to each other. Each connection forms a Router-Router subnet with only 2 interfaces.

On the other hand, each router is connected with a laptop separately named as BT001, BT002 and BT003 and thus forms a Router-Laptop subnet. A customer of BT Network is assigned with a Router-Laptop subnet and has a minimum of 10 host IP addresses.

To connect to neighbouring ISPs, a Router-Neighbour subnet is formed for each connection. Concretely, Router 2 (BT-R002) is connected to one of DT Network's routers while Router 3 (BT-R003) is connected to one of Virgin Network's and Central Network's routers separately.

All of the above connections are through physical cables.

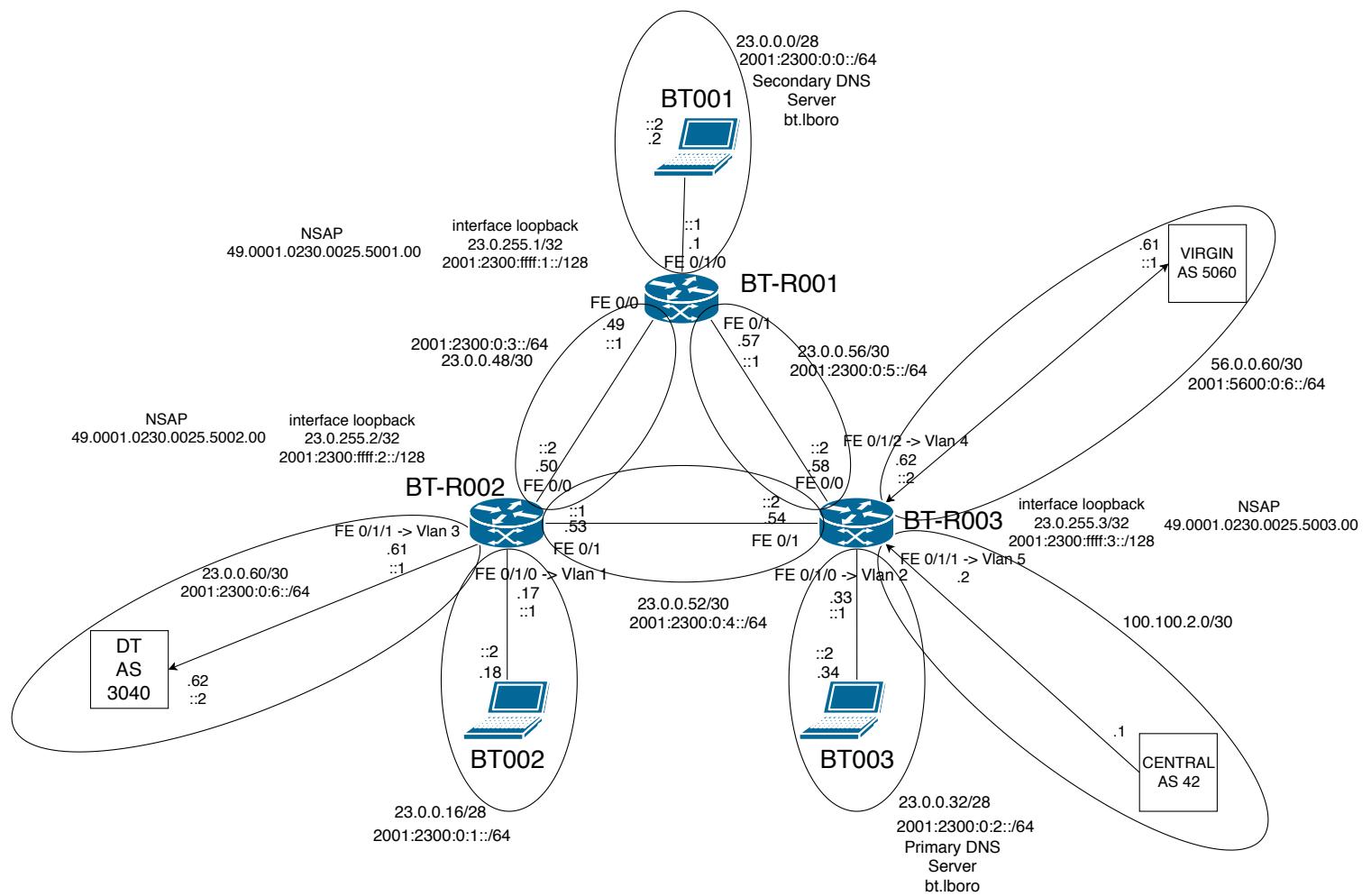


Figure 2.1: Full Network Diagram of BT Network.

2.1.2 IP Addresses and Interfaces

An IPv4 address range of $23.0.0.0/8$ and IPv6 address range of $2001:2300::/32$ are allocated to BT Network, which are further divided into sub-ranges to be allocated to each subnet.

For IPv4 addressing, a prefix of n is needed for a subnet that demands X host addresses, where n is an integer that satisfies $2^{32-n} - 2 \geq X$ and $n \leq 32$. For our lab, the maximum value for prefix is used in order to minimize the size of each subnet and reserve address space for future customers. **However, it's also possible to use a larger value for each Router-Laptop subnet in order to maximize the size of the subnet, given that the number of customers (in this case, 3) is fixed.**

In BT Network, the prefix for each Router-Router and Router-Neighbour subnet is 30 while the prefix for each Router-Laptop subnet is 28. In other words, each Router-Router and Router-Neighbour subnet has 2 guaranteed IPv4 host addresses while each Router-Laptop subnet has 14 guaranteed IPv4 host addresses. During address block allocation, larger subnet is being considered before smaller one reduce the number of block segments.

For IPv6 addressing, however, each subnet has a fixed prefix of 64 to ensure that each interface in the subnet has a unique address. The full details of IP address allocation is shown in Table 2.1.

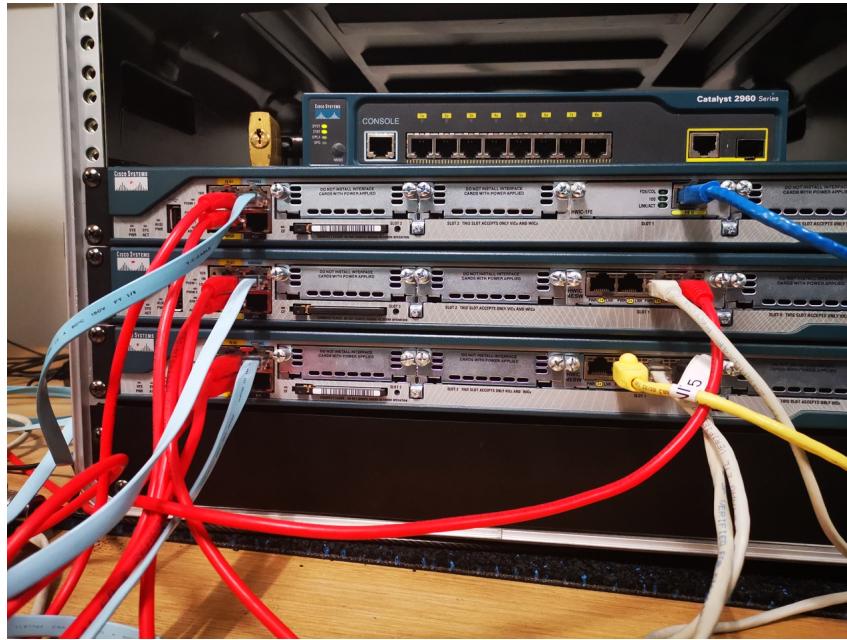


Figure 2.2: Physical Connections within BT Network.

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In terms of interfaces, there are 3 Ethernet interfaces (**FastEthernet0/0**, **FastEthernet0/1** and **FastEthernet0/1/0**) on Router 1, each of which can be assigned with an IP address. On Router 2 and 3, however, there are 6 Ethernet interfaces each and only 2 of them (**FastEthernet0/0** and **FastEthernet0/1**) can be directly assigned with IP addresses. The remaining 4 interfaces are link layer interfaces and thus does not possess any IP address. To be assigned with an IP address, such an interface need to be assigned to an Virtual LAN (VLAN) to which the address is actually assigned.

Router-Router connections are established through either **FastEthernet0/0** or **FastEthernet0/1** interfaces on both ends while Router-Laptop and Router-Neighbour are through one of the remaining interfaces on the router end. Since both interfaces are on the left-hand side of each router and such arrangement helps distinguishing between Router-Router connections and others easily as shown in Figure 2.2. Interfaces of both ends for each connection as well as their corresponding IP addresses are detailed in Table 2.2.

Subnet	IPv4 Address / Prefix	IPv4 Address Range	IPv6 Address / Prefix	IPv6 Address Range
BT-R001 - BT001	23.0.0.0/28	23.0.0.1 - 23.0.0.14	2001:2300:0:0::/64	2001:2300:0:0::1 - 2001:2300:0:0:ffff:ffff:ffff:fffe
BT-R002 - BT002	23.0.0.16/28	23.0.0.17 - 23.0.0.30	2001:2300:0:1::/64	2001:2300:0:1::1 - 2001:2300:0:1:ffff:ffff:ffff:fffe
BT-R003 - BT003	23.0.0.32/28	23.0.0.33 - 23.0.0.62	2001:2300:0:2::/64	2001:2300:0:2::1 - 2001:2300:0:2:ffff:ffff:ffff:fffe
BT-R001 - BT-R002	23.0.0.48/30	23.0.0.49 - 23.0.0.50	2001:2300:0:3::/64	2001:2300:0:3::1 - 2001:2300:0:3:ffff:ffff:ffff:fffe
BT-R002 - BT-R003	23.0.0.52/30	23.0.0.53 - 23.0.0.54	2001:2300:0:4::/64	2001:2300:0:4::1 - 2001:2300:0:4:ffff:ffff:ffff:fffe
BT-R001 - BT-R003	23.0.0.56/30	23.0.0.57 - 23.0.0.58	2001:2300:0:5::/64	2001:2300:0:5::1 - 2001:2300:0:5:ffff:ffff:ffff:fffe
BT-R002 - DT	23.0.0.60/30	23.0.0.61 - 23.0.0.62	2001:2300:0:6::/64	2001:2300:0:6::1 - 2001:2300:0:6:ffff:ffff:ffff:fffe
BT-R003 - Virgin	56.0.0.60/30	56.0.0.61 - 56.0.0.62	2001:5600:0:6::/64	2001:5600:0:6::1 - 2001:5600:0:6:ffff:ffff:ffff:fffe
BT-R003 - Central	100.100.2.0/30	100.100.2.1 - 100.100.2.2		

Table 2.1: Allocation of IPv4 and IPv6 Addresses to Subnets in BT Network.

Connection	Interface 1	IPv4 Address	IPv6 Address	Interface 2	IPv4 Address	IPv6 Address
BT-R001 - BT001	BT-R001: FastEthernet0/1/0	23.0.0.1	2001:2300:0:0::1	BT001: eth0	23.0.0.2	2001:2300:0:0::2
BT-R002 - BT002	BT-R002: FastEthernet0/1/0 -> Vlan 1	23.0.0.17	2001:2300:0:1::1	BT002: eth0	23.0.0.18	2001:2300:0:1::2
BT-R003 - BT003	BT-R003: FastEthernet0/1/0 -> Vlan 2	23.0.0.33	2001:2300:0:2::1	BT003: eth0	23.0.0.34	2001:2300:0:2::2
BT-R001 - BT-R002	BT-R001: FastEthernet0/0	23.0.0.49	2001:2300:0:3::1	BT-R002: FastEthernet0/0	23.0.0.50	2001:2300:0:3::2
BT-R002 - BT-R003	BT-R002: FastEthernet0/1	23.0.0.53	2001:2300:0:4::1	BT-R003: FastEthernet0/1	23.0.0.54	2001:2300:0:4::2
BT-R001 - BT-R003	BT-R001: FastEthernet0/1	23.0.0.57	2001:2300:0:5::1	BT-R003: FastEthernet0/0	23.0.0.58	2001:2300:0:5::2
BT-R002 - DT	BT-R002: FastEthernet0/1/1 -> Vlan 3	23.0.0.61	2001:2300:0:6::1	DT	23.0.0.62	2001:2300:0:6::2
BT-R003 - Virgin	BT-R003: FastEthernet0/1/2 -> Vlan 4	56.0.0.62	2001:5600:0:6::2	Virgin	56.0.0.61	2001:5600:0:6::1
BT-R003 - Central	BT-R003: FastEthernet0/1/1 -> Vlan 5	100.100.2.2		Central	100.100.2.1	

Table 2.2: Interfaces for Each Physical Connection and Corresponding IPv4 and IPv6 Addresses.

2.2 IP Addresses of Interfaces

Assigning IP addresses[1][2] to interfaces should be the first step in building BT Network since all network services listed in 1.1 cannot operate without IP addresses. The assignment of IP addresses in Table 2.1 and 2.2 is implemented.

2.2.1 Implementation

2.2.1.1 Routers

For Router 1 (BT-R001), IP addresses are assigned directly to physical interfaces as all interfaces are network layer interfaces.

```
1 int fa0/0
2 ip address 23.0.0.49 255.255.255.252
3 ipv6 address 2001:2300:0:3::1/64
4 no shutdown
5
6 int fa0/1
7 ip address 23.0.0.57 255.255.255.252
8 ipv6 address 2001:2300:0:5::1/64
9 no shutdown
10
11 int fa0/1/0
12 ip address 23.0.0.1 255.255.255.240
13 ipv6 address 2001:2300:0:0::1/64
14 no shutdown
```

For Router 2 (BT-R002), however, only 2 interfaces (**FastEthernet0/0** and **FastEthernet0/1**) each are network layer interfaces. The remaining 4 interfaces are link layer interfaces and need to be assigned to an VLAN separately so where an IP address can be assigned.

```
1 int fa0/0
2 ip address 23.0.0.50 255.255.255.252
3 ipv6 address 2001:2300:0:3::2/64
4 no shutdown
5
6 int fa0/1
7 ip address 23.0.0.53 255.255.255.252
8 ipv6 address 2001:2300:0:4::1/64
9 no shutdown
10
11 vlan 1
12 int fa0/1/0
13 switchport mode access
14 switchport access vlan 1
```

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```
15 int vlan 1
16 ip address 23.0.0.17 255.255.255.240
17 ipv6 address 2001:2300:0:1::1/64
18 no shutdown
19
20 vlan 3
21 int fa0/1/1
22 switchport mode access
23 switchport access vlan 3
24 int vlan 3
25 ip address 23.0.0.61 255.255.255.252
26 ipv6 address 2001:2300:0:6::1/64
27 no shutdown
```

Similarly, IP addresses are assigned to Router 3 (BT-R003).

```
1 int fa0/0
2 ip address 23.0.0.58 255.255.255.252
3 ipv6 address 2001:2300:0:5::2/64
4 no shutdown
5
6 int fa0/1
7 ip address 23.0.0.54 255.255.255.252
8 ipv6 address 2001:2300:4::2/64
9 no shutdown
10
11 vlan 2
12 int fa0/1/0
13 switchport mode access
14 switchport access vlan 2
15 int vlan 2
16 ip address 23.0.0.33 255.255.255.240
17 ipv6 address 2001:2300:0:2::1/64
18 no shutdown
19
20 vlan 4
21 int fa0/1/2
22 switchport mode access
23 switchport access vlan 4
24 int vlan 4
25 ip address 56.0.0.62 255.255.255.252
26 ipv6 address 2001:5600:0:6::2/64
27 no shutdown
28
29 vlan 5
30 int fa0/1/1
31 switchport mode access
32 switchport access vlan 5
```

```
33 int vlan 5
34 ip address 100.100.2.2 255.255.255.252
35 no shutdown
```

2.2.1.2 Laptops

Unlike routers, the IP assignment of laptops' interfaces are more aligned since all laptops are of the same model. On Laptop 1 (BT001), the file `/etc/network/interface` is edited as follows before rebooting to apply changes. Similarly, IP address can be assigned to Laptop 2's (BT002) and Laptop 3's (BT003) interfaces respectively.

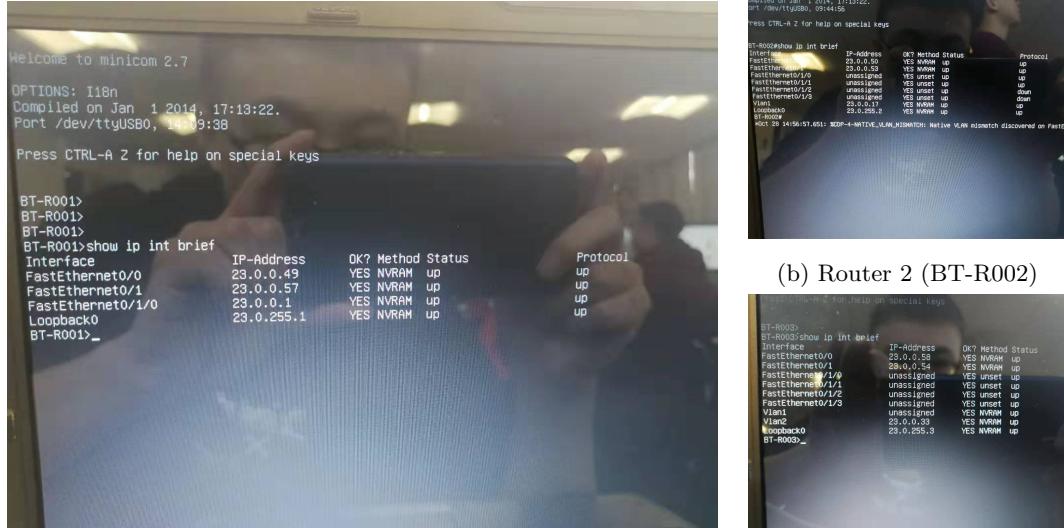
```
1 auto lo
2 iface lo inet loopback
3 auto eth0
4 ifacce eth0 inet static
5 address 23.0.0.2
6 netmask 255.255.255.240
7 gateway 23.0.0.1
8
9 ifacce eth0 inet6 static
10 address 2001:2300::2
11 netmask 64
12 gateway 2001:2300::1
```

2.2.2 Evaluation

On all 3 routers, the implementation of IP assignments is evaluated using `show ip int brief` and `show ipv6 int brief`. These 2 commands show IPv4 and IPv6 addresses of interfaces on routers respectively. Successful assignment of IP addresses to routers' interfaces is evident from Figure 2.3 and 2.4.

On the laptops' side, the implementation of IP assignments is evaluated using `ifconfig` command. Successful assignment of IP addresses to laptops' interfaces is evident from Figure 2.5.

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(a) Router 1 (BT-R001)

```
Welcome to minicom 2.7
OPTIONS: I18n
Compiled on Jan 1 2014, 17:13:22.
Port /dev/ttyUSB0, 1449384 bps

Press CTRL-A Z for help on special keys

BT-R001>
BT-R001>
BT-R001>show ip int brief
Interface          IP-Address      OK? Method Status       Protocol
FastEthernet0/0    23.0.0.49      YES NVRAM up        up
FastEthernet0/1    23.0.0.57      YES NVRAM up        up
FastEthernet0/1/0   23.0.0.1       YES NVRAM up        up
Loopback0          23.0.255.1    YES NVRAM up        up
BT-R001>
```

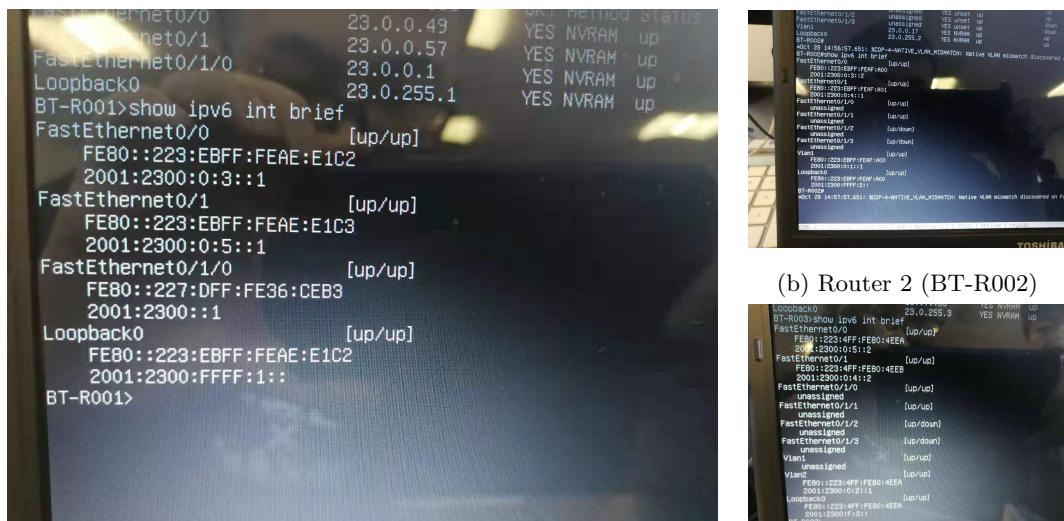
(b) Router 2 (BT-R002)

```
BT-R002#show ip int brief
Interface          IP-Address      OK? Method Status       Protocol
FastEthernet0/0    23.0.0.49      YES NVRAM up        up
FastEthernet0/1    23.0.0.53      YES NVRAM up        up
FastEthernet0/1/0   unassigned     YES unset up        up
FastEthernet0/1/1   unassigned     YES unset up        down
FastEthernet0/1/2   unassigned     YES unset up        down
FastEthernet0/1/3   unassigned     YES unset up        down
FastEthernet0/1/4   unassigned     YES unset up        down
Loopback0          23.0.255.2    YES NVRAM up        up
BT-R002#
```

(c) Router 3 (BT-R003)

```
BT-R003#show ip int brief
Interface          IP-Address      OK? Method Status       Protocol
FastEthernet0/0    23.0.0.49      YES NVRAM up        up
FastEthernet0/1    23.0.0.54      YES NVRAM up        up
FastEthernet0/1/0   unassigned     YES unset up        up
FastEthernet0/1/1   unassigned     YES unset up        up
FastEthernet0/1/2   unassigned     YES unset up        up
FastEthernet0/1/3   unassigned     YES unset up        up
Vlan2              23.0.0.33      YES NVRAM up        up
Loopback0          23.0.255.3    YES NVRAM up        up
BT-R003#
```

Figure 2.3: Successful Assignment of IPv4 Addresses to Routers' Interfaces.



(a) Router 1 (BT-R001)

```
BT-R001>show ipv6 int brief
FastEthernet0/0      23.0.0.49      YES NVRAM up        [up/up]
FastEthernet0/1      23.0.0.57      YES NVRAM up        [up/up]
FastEthernet0/1/0    23.0.0.1       YES NVRAM up        [up/up]
Loopback0           23.0.255.1    YES NVRAM up        [up/up]
BT-R001>show ipv6 int brief
FastEthernet0/0      FE80::223:EBFF:FEAE:E1C2
2001:2300:0:3::1   YES NVRAM up        [up/up]
FastEthernet0/1      FE80::223:EBFF:FEAE:E1C3
2001:2300:0:5::1   YES NVRAM up        [up/up]
FastEthernet0/1/0    FE80::227:DFF:FE36:CEB3
2001:2300::1       YES NVRAM up        [up/up]
Loopback0           FE80::223:EBFF:FEAE:E1C2
2001:2300:FFFF:1:: YES NVRAM up        [up/up]
BT-R001>
```

(b) Router 2 (BT-R002)

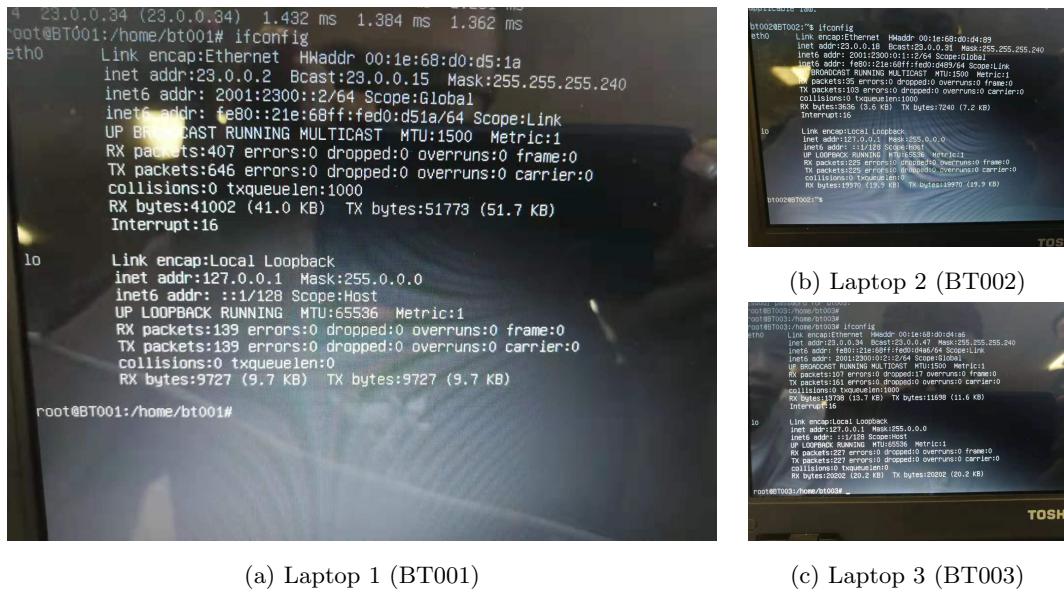
```
BT-R002#show ipv6 int brief
FastEthernet0/0      FE80::223:4FF:FE80::4EEA
2001:2300:0:1::1    YES NVRAM up        [up/up]
FastEthernet0/1      FE80::223:4FF:FE80::4EEB
2001:2300:0:14::2   YES NVRAM up        [up/up]
FastEthernet0/1/0    unassigned     YES unset up        [up/up]
FastEthernet0/1/1    unassigned     YES unset up        [up/up]
FastEthernet0/1/2    unassigned     YES unset up        [up/down]
FastEthernet0/1/3    unassigned     YES unset up        [up/down]
FastEthernet0/1/4    unassigned     YES unset up        [up/down]
Vlan2               2001:2300:0:1::11   YES NVRAM up        [up/up]
Loopback0           FE80::223:4FF:FE80::4EEA
2001:2300:0:10::11  YES NVRAM up        [up/up]
FastEthernet0/0      FE80::223:4FF:FE80::4EEB
2001:2300:0:11::1   YES NVRAM up        [up/up]
BT-R002#
```

(c) Router 3 (BT-R003)

```
BT-R003#show ipv6 int brief
FastEthernet0/0      FE80::223:4FF:FE80::4EEA
2001:2300:0:10::11  YES NVRAM up        [up/up]
FastEthernet0/1      FE80::223:4FF:FE80::4EEB
2001:2300:0:11::1   YES NVRAM up        [up/up]
FastEthernet0/1/0    unassigned     YES unset up        [up/up]
FastEthernet0/1/1    unassigned     YES unset up        [up/up]
FastEthernet0/1/2    unassigned     YES unset up        [up/up]
FastEthernet0/1/3    unassigned     YES unset up        [up/up]
Vlan2               2001:2300:0:1::11   YES NVRAM up        [up/up]
Loopback0           FE80::223:4FF:FE80::4EEA
2001:2300:0:10::11  YES NVRAM up        [up/up]
FastEthernet0/0      FE80::223:4FF:FE80::4EEB
2001:2300:0:11::1   YES NVRAM up        [up/up]
BT-R003#
```

Figure 2.4: Successful Assignment of IPv6 Addresses to Routers' Interfaces.

CHAPTER 2. NETWORK ARCHITECTURE



(a) Laptop 1 (BT001)

```

root@BT001:/home/bt001# ifconfig
eth0      Link encap:Ethernet HWaddr 00:1e:68:d0:d5:18
          inet addr:23.0.0.2 Bcast:23.0.0.15 Mask:255.255.255.240
          inet6 addr: 2001:2300:10::1:2/64 Scope:Global
            inet6 addr: fe80::21e:68ff:fed0:d51a/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST MTU:1500 Metric:1
          RX packets:407 errors:0 dropped:0 overruns:0 frame:0
          TX packets:646 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:41002 (41.0 KB) TX bytes:51773 (51.7 KB)
          Interrupt:16

lo       Link encap:Local Loopback
          inet addr:127.0.0.1 Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING MTU:65536 Metric:1
          RX packets:139 errors:0 dropped:0 overruns:0 frame:0
          TX packets:139 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:9727 (9.7 KB) TX bytes:9727 (9.7 KB)

root@BT001:/home/bt001#

```

(b) Laptop 2 (BT002)

```

root@BT002:/home/bt002# ifconfig
eth0      Link encap:Ethernet HWaddr 00:1e:68:d0:d5:24
          inet addr:23.0.0.3 Bcast:23.0.0.15 Mask:255.255.255.240
          inet6 addr: 2001:2300:10::1:3/64 Scope:Global
            inet6 addr: fe80::21e:68ff:fed0:d524/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST MTU:1500 Metric:1
          RX packets:109 errors:0 dropped:0 overruns:0 frame:0
          TX packets:109 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:9728 (9.7 KB) TX bytes:11690 (11.6 KB)
          Interrupt:16

lo       Link encap:Local Loopback
          inet addr:127.0.0.1 Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING MTU:65536 Metric:1
          RX packets:107 errors:0 dropped:17 overruns:0 frame:0
          TX packets:107 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:9728 (9.7 KB) TX bytes:11690 (11.6 KB)
          Interrupt:16

root@BT002:/home/bt002#

```

(c) Laptop 3 (BT003)

```

root@BT003:/home/bt003# ifconfig
eth0      Link encap:Ethernet HWaddr 00:1e:68:d0:d5:24
          inet addr:23.0.0.4 Bcast:23.0.0.15 Mask:255.255.255.240
          inet6 addr: 2001:2300:10::1:4/64 Scope:Global
            inet6 addr: fe80::21e:68ff:fed0:d524/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST MTU:1500 Metric:1
          RX packets:227 errors:0 dropped:0 overruns:0 frame:0
          TX packets:227 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:20202 (20.2 KB) TX bytes:20202 (20.2 KB)

lo       Link encap:Local Loopback
          inet addr:127.0.0.1 Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING MTU:65536 Metric:1
          RX packets:107 errors:0 dropped:0 overruns:0 frame:0
          TX packets:107 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:0
          RX bytes:9728 (9.7 KB) TX bytes:11690 (11.6 KB)
          Interrupt:16

root@BT003:/home/bt003#

```

Figure 2.5: Successful Assignment of IPv4 and IPv6 Addresses to Laptops' Interfaces.

Chapter 3

Routing Protocols in the Network

3.1 Intra-domain Routing Protocol: IS-IS

3.1.1 Design

Due to the limitation of the static routing, routers cannot find alternative paths if a set path is broken and thus a new path need to be set manually. In contrast, dynamic routing always finds the least cost path even when the previous least cost path is broken. Popular dynamic routing protocols include distance vector based protocols like Routing Information Protocol (RIP)[3] and link state based protocols like Intermediate System to Intermediate System (IS-IS)[4] and Open Shortest Path First (OSPF)[5].

In this lab, the IS-IS is used as the Interior Gateway Protocol (IGP), which provides faster convergence and larger scalability compared to distance vector based protocols. IS-IS is short for Intermediate System to Intermediate System Routing Protocol. By using this protocol, each router maintains a database which has a map of the whole topology and all routers have the same information. The best path to every destination is computed by all routers. Figure 3.1 shows the design of IS-IS protocol in BT Network. As the figure shows, the network only has level-1 routers for internal routing.

3.1.2 Loopback Addresses and NSAP for Routers

To set up IS-IS, an unique loopback address is needed for each router. An IPv4 address block of 23.0.255.0/24 and IPv6 address block of 2001:2300:ffff::/48 is allocated for loopback addresses.

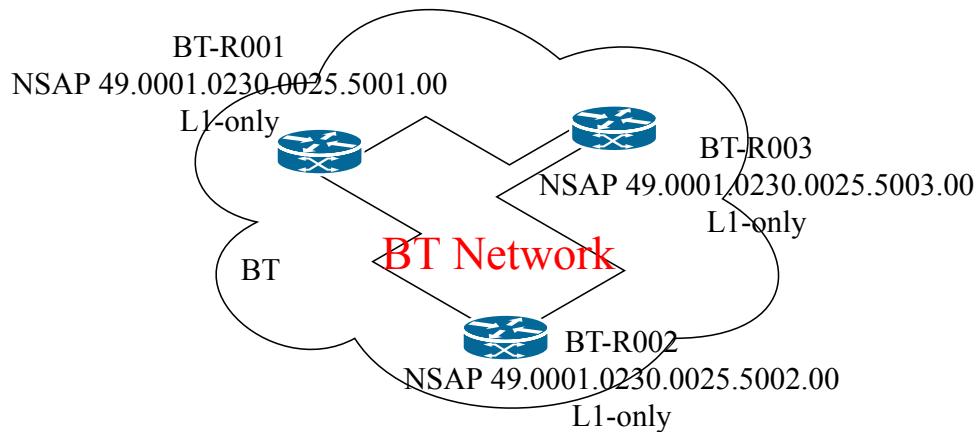


Figure 3.1: Design of IS-IS Protocol in BT Network.

Following the CLNS addressing convention, each router is then assigned with a NSAP. A NSAP has 3 main components.

According to the convention, the leading Area ID is composed of AFI (49) and Area Address (0001). The System ID followed is set to the IPv4 loopback address of the router. If the loopback address is *ABC.DEF.GHI.JKL*, then System ID should be *ABCD.EFGH.IJKL*. The last main component is N-Selector (NSEL) and set to 00.

The assignment of addresses and NSAP to routers are detailed in Table 3.1.

Router	IPv4 Loopback Address	IPv6 Loopback Address	NSAP
BT-R001	23.0.255.1	2001:2300:ffff:1::	49.0001.0230.0025.5001.00
BT-R002	23.0.255.2	2001:2300:ffff:2::	49.0001.0230.0025.5002.00
BT-R003	23.0.255.3	2001:2300:ffff:3::	49.0001.0230.0025.5003.00

Table 3.1: IP Loopback Addresses and NSAP for Routers in BT Network.

3.1.3 Implementation

IS-IS is set up on Router 1 (BT-R001) using the following commands.

```

1 interface Loopback0
2 ip address 23.0.255.1 255.255.255.255
3 ipv6 address 2001:2300:FFFF:1::/128
4
5 router isis
6 net 49.0001.0230.0025.5001.00
7 is-type level-1

```

Then, IS-IS is turned on on all interfaces to internal routers.

```

1 interface FastEthernet0/0
2 ip router isis
3 ipv6 router isis
4
5 interface FastEthernet0/1
6 ip router isis
7 ipv6 router isis
8

```

CHAPTER 3. ROUTING PROTOCOLS IN THE NETWORK

However, IS-IS routes should not be broadcasted nor received through the loopback interface (`Loopback0`) while the route to corresponding subnet should be broadcasted to other internal routers. Therefore, the loopback interface should be a passive interface in IS-IS protocol.

```
1 router isis
2 passive-interface Loopback0
```

For Router 2 (BT-R002) and Router 3 (BT-R002), IS-IS is set up similarly using the above commands. The main difference is that interfaces to external routers (VLAN 3 for Router 2 and VLAN 4 & 5 for Router 3) should be passive interfaces as well. Below is the configuration for Router 2.

```
1 interface Loopback0
2 ip address 23.0.255.2 255.255.255.255
3 ipv6 address 2001:2300:FFFF:2::/128
4
5 router isis
6 net 49.0001.0230.0025.5002.00
7 is-type level-1
8 passive-interface Vlan3
9 passive-interface Loopback0
10
11 interface FastEthernet0/0
12 ip router isis
13 ipv6 router isis
14
15 interface FastEthernet0/1
16 ip router isis
17 ipv6 router isis
18
19 interface Vlan1
20 ip router isis
21 ipv6 router isis
```

Below is the configuration for Router 3.

```
1 interface Loopback0
2 ip address 23.0.255.3 255.255.255.255
3 ipv6 address 2001:2300:FFFF:3::/128
4
5 router isis
6 net 49.0001.0230.0025.5003.00
7 is-type level-1
8 passive-interface Vlan4
9 passive-interface Vlan5
10 passive-interface Loopback0
```

```
11
12 interface FastEthernet0/0
13 ip router isis
14 ipv6 router isis
15
16 interface FastEthernet0/1
17 ip router isis
18 ipv6 router isis
19
20 interface Vlan2
21 ip router isis
22 ipv6 router isis
```

3.1.4 Evaluation

Once the IS-IS is set up, use **traceroute** command to check the IPv4 path from Laptop 1 (BT001, IPv4 Address: 23.0.0.2) to Laptop 2 (BT002, IPv4 Address: 23.0.0.18) in the network.

```
1 traceroute 23.0.0.34
```

Figure 3.2 shows the route taken is Laptop 1 (BT001, IPv4 Address: 23.0.0.2) -> Router 1 (BT-R001, IPv4 Address: 23.0.0.1) -> Router 2 (BT-R002, IPv4 Address: 23.0.0.50) -> Laptop 2 (BT002, IPv4 Address: 23.0.0.18), which is a correct route. Routes from Laptop 1 to Laptop 3 as well as from Laptop 2 to Laptop 3 are tested and shown in the figure as well.

Similiar results can be observed for IPv6 routes in Figure 3.3. The IPv6 Route taken from Laptop 1 to Laptop 2 is Laptop 1 (BT001, IPv6 Address: 2001:2300::2) -> Router 1 (BT-R001, IPv6 Address: 2001:2300::1) -> Router 2 (BT-R002, IPv6 Address: 2001:2300:3:2::2) -> Laptop 2 (BT002, IPv6 Address: 2001:2300:0:1::2), , which is also a correct route. Routes from Laptop 1 to Laptop 3 as well as from Laptop 2 to Laptop 3 are tested and shown in the figure as well.

```
root@BT001:/home/bt001# traceroute 23.0.0.18
traceroute to 23.0.0.18 (23.0.0.18), 30 hops max, 60 byte packets
 1  23.0.0.33 (23.0.0.33)  1.070 ms  1.643 ms  2.137 ms
 2  23.0.0.53 (23.0.0.53)  1.572 ms  1.980 ms  2.069 ms
 3  23.0.0.18 (23.0.0.18)  1.044 ms  1.023 ms  0.991 ms
root@BT001:/home/bt001# -
```

(a) traceroute from Laptop 1 (BT001) to Laptop 2 (BT002)

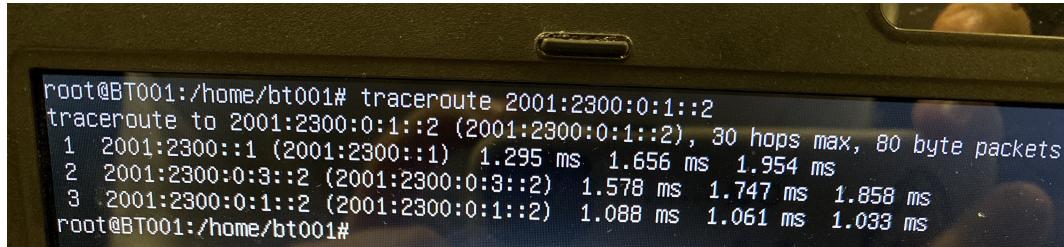
```
root@BT001:/home/bt001# traceroute 23.0.0.34
traceroute to 23.0.0.34 (23.0.0.34), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.073 ms  1.602 ms  1.840 ms
 2  23.0.0.58 (23.0.0.58)  1.208 ms  1.943 ms  2.264 ms
 3  23.0.0.34 (23.0.0.34)  1.850 ms  1.830 ms  1.809 ms
root@BT001:/home/bt001# -
```

(b) traceroute from Laptop 1 (BT001) to Laptop 3 (BT003)

```
root@BT002:/home/bt002# traceroute 23.0.0.34
traceroute to 23.0.0.34 (23.0.0.34), 30 hops max, 60 byte packets
 1  23.0.0.17 (23.0.0.17)  1.006 ms  1.542 ms  1.959 ms
 2  23.0.0.54 (23.0.0.54)  0.981 ms  2.216 ms  2.451 ms
 3  23.0.0.34 (23.0.0.34)  1.856 ms  1.843 ms  1.924 ms
root@BT002:/home/bt002# -
```

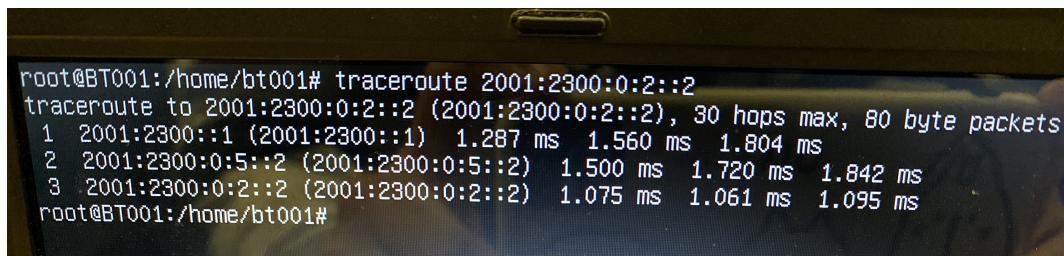
(c) traceroute from Laptop 2 (BT002) to Laptop 3 (BT003)

Figure 3.2: Tracing IPv4 Routes between Laptops using traceroute.



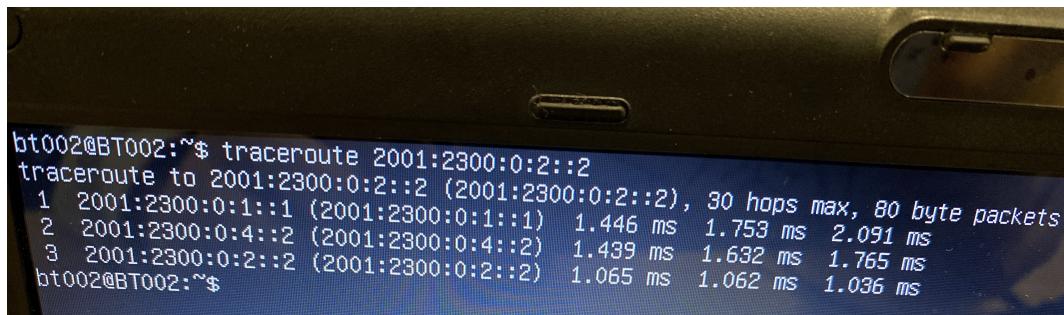
```
root@BT001:/home/bt001# traceroute 2001:2300:0:1::2
traceroute to 2001:2300:0:1::2 (2001:2300:0:1::2), 30 hops max, 80 byte packets
 1  2001:2300::1 (2001:2300::1)  1.295 ms  1.656 ms  1.954 ms
 2  2001:2300:0:3::2 (2001:2300:0:3::2)  1.578 ms  1.747 ms  1.858 ms
 3  2001:2300:0:1::2 (2001:2300:0:1::2)  1.088 ms  1.061 ms  1.033 ms
root@BT001:/home/bt001#
```

(a) traceroute from Laptop 1 (BT001) to Laptop 2 (BT002)



```
root@BT001:/home/bt001# traceroute 2001:2300:0:2::2
traceroute to 2001:2300:0:2::2 (2001:2300:0:2::2), 30 hops max, 80 byte packets
 1  2001:2300::1 (2001:2300::1)  1.287 ms  1.560 ms  1.804 ms
 2  2001:2300:0:5::2 (2001:2300:0:5::2)  1.500 ms  1.720 ms  1.842 ms
 3  2001:2300:0:2::2 (2001:2300:0:2::2)  1.075 ms  1.061 ms  1.095 ms
root@BT001:/home/bt001#
```

(b) traceroute from Laptop 1 (BT001) to Laptop 3 (BT003)



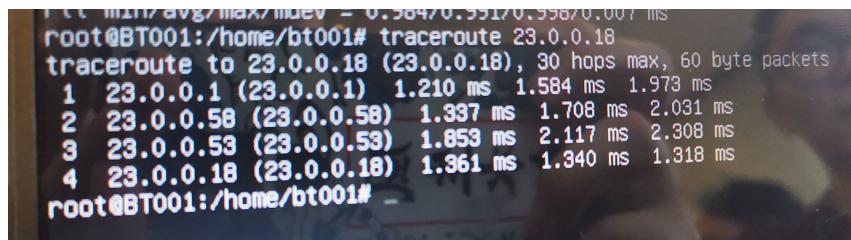
```
bt002@BT002:~$ traceroute 2001:2300:0:2::2
traceroute to 2001:2300:0:2::2 (2001:2300:0:2::2), 30 hops max, 80 byte packets
 1  2001:2300:0:1::1 (2001:2300:0:1::1)  1.446 ms  1.753 ms  2.091 ms
 2  2001:2300:0:4::2 (2001:2300:0:4::2)  1.439 ms  1.632 ms  1.765 ms
 3  2001:2300:0:2::2 (2001:2300:0:2::2)  1.065 ms  1.062 ms  1.036 ms
bt002@BT002:~$
```

(c) traceroute from Laptop 2 (BT002) to Laptop 3 (BT003)

Figure 3.3: Tracing IPv6 Routes between Laptops using traceroute.

To further evaluate the correctness of our implementation, we check the path from Laptop 1 to Laptop 2 under the condition that the physical connection between Router 1 and Router 2 is broken. The IS-IS protocol on Router 1 should be able to find route to Router 2 through Router 3.

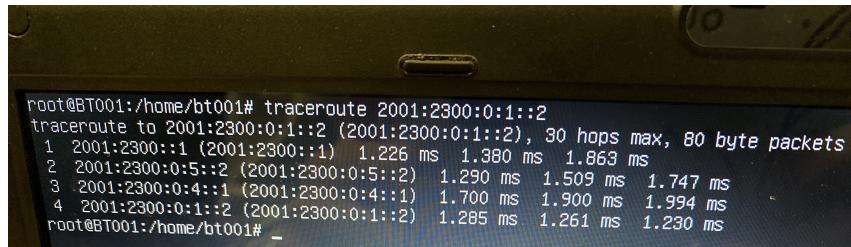
Figure 3.4 shows the IPv4 route taken is Laptop 1 (BT001, IPv6 Address: 23.0.0.2) -> Router 1 (BT-R001, IPv4 Address: 23.0.0.1) -> Router 3 (BT-R003, IPv4 Address: 23.0.0.58) -> Router 2 (BT-R002, IPv4 Address: 23.0.0.53) -> Laptop 2 (BT002, IPv4 Address: 23.0.0.18), which is a correct route.



```
root@BT001:/home/bt001# traceroute 23.0.0.18
traceroute to 23.0.0.18 (23.0.0.18), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.210 ms  1.584 ms  1.973 ms
 2  23.0.0.58 (23.0.0.58)  1.337 ms  1.708 ms  2.031 ms
 3  23.0.0.53 (23.0.0.53)  1.853 ms  2.117 ms  2.308 ms
 4  23.0.0.18 (23.0.0.18)  1.361 ms  1.340 ms  1.318 ms
root@BT001:/home/bt001#
```

Figure 3.4: Tracing IPv4 Routes from Laptop 2 (BT002) to Laptop 3 (BT003) when Physical Connection between Router 1 (BT-R001) and Router 2 (BT-R002) is broken.

Figure 3.5 shows the IPv6 route taken is Laptop 1 (BT001, IPv6 Address: 2001:2300::2) -> Router 1 (BT-R001, IPv6 Address: 2001:2300::1) -> Router 3 (BT-R003, IPv6 Address: 2001:2300:0:5::2) -> Router 2 (BT-R002, IPv6 Address: 2001:2300:0:4::1) -> Laptop 2 (BT002, IPv6 Address: 2001:2300:0:1::2), which is also a correct route.

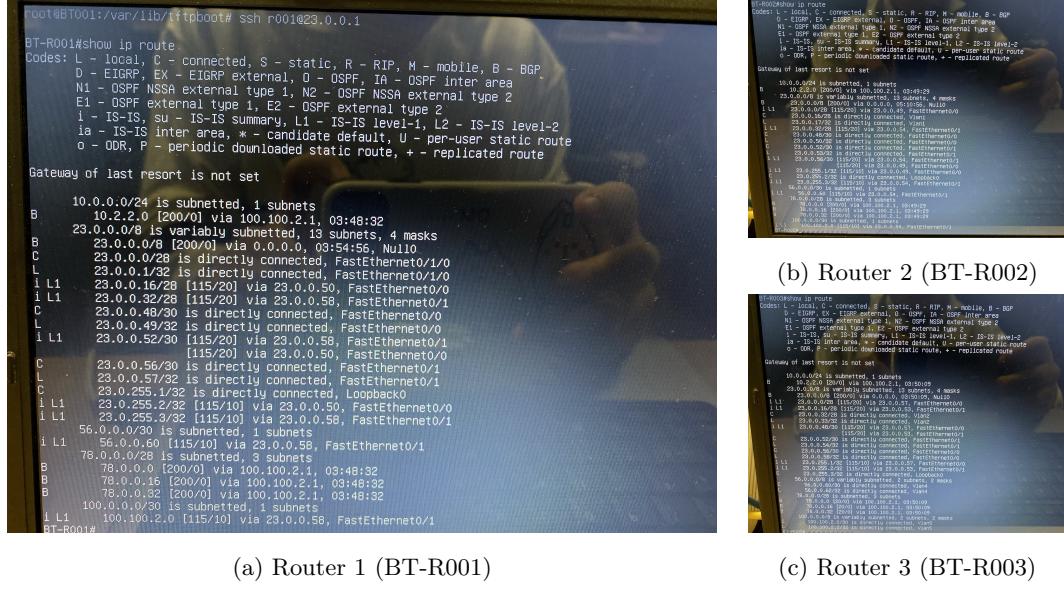


```
root@BT001:/home/bt001# traceroute 2001:2300:0:1::2
traceroute to 2001:2300:0:1::2 (2001:2300:0:1::2), 30 hops max, 80 byte packets
 1  2001:2300::1 (2001:2300::1)  1.226 ms  1.380 ms  1.863 ms
 2  2001:2300:0:5::2 (2001:2300:0:5::2)  1.290 ms  1.509 ms  1.747 ms
 3  2001:2300:0:4::1 (2001:2300:0:4::1)  1.700 ms  1.900 ms  1.994 ms
 4  2001:2300:0:1::2 (2001:2300:0:1::2)  1.285 ms  1.261 ms  1.230 ms
root@BT001:/home/bt001#
```

Figure 3.5: Tracing IPv6 Routes from Laptop 2 (BT002) to Laptop 3 (BT003) when Physical Connection between Router 1 (BT-R001) and Router 2 (BT-R002) is broken.

CHAPTER 3. ROUTING PROTOCOLS IN THE NETWORK

On the router's side, `show ip route` and `show ipv6 route` is used to inspect the routes discovered by IS-IS protocol. In Figure 3.6 and 3.7, such routes to other subnets inside BT Network on each router are shown.



(a) Router 1 (BT-R001)

```

root@BT-R001:/var/lib/tftpboot# ssh r001@23.0.0.1
BT-R001#show ip route
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
      D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
      N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
      E1 - OSPF external type 1, E2 - OSPF external type 2
      L1 - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
      ia - IS-IS inter area, * - candidate default, U - per-user static route
      o - ODR, P - periodic downloaded static route, + - replicated route
Gateway of last resort is not set

10.0.0.0/24 is subnetted, 1 subnets
B 10.2.2.0 [200/0] via 100.100.2.1, 03:48:32
23.0.0.0/8 is variably subnetted, 13 subnets, 4 masks
B 23.0.0.0/8 [200/0] via 0.0.0.0, 03:54:56, Null0
C 23.0.0.0/28 is directly connected, FastEthernet0/1/0
L 23.0.0.1/32 is directly connected, FastEthernet0/1/0
I L1 23.0.0.16/28 [115/20] via 23.0.0.50, FastEthernet0/0
I L1 23.0.0.32/28 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.48/30 is directly connected, FastEthernet0/0
L 23.0.0.49/32 is directly connected, FastEthernet0/0
I L1 23.0.0.52/30 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.56/30 is directly connected, FastEthernet0/1
L 23.0.0.57/32 is directly connected, FastEthernet0/1
C 23.0.255.1/32 is directly connected, Loopback0
I L1 23.0.255.2/32 [115/10] via 23.0.0.50, FastEthernet0/0
I L1 23.0.255.3/32 [115/10] via 23.0.0.58, FastEthernet0/1
56.0.0.0/30 is subnetted, 1 subnets
I L1 56.0.0.60 [115/10] via 23.0.0.58, FastEthernet0/1
78.0.0.0/28 is subnetted, 3 subnets
B 78.0.0.0 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.16 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.32 [200/0] via 100.100.2.1, 03:48:32
    100.0.0.30 is subnetted, 1 subnets
I L1 100.100.2.0 [115/10] via 23.0.0.58, FastEthernet0/1
BT-R001#

```

(b) Router 2 (BT-R002)

```

BT-R002#show ip route
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
      D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
      N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
      E1 - OSPF external type 1, E2 - OSPF external type 2
      L1 - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
      ia - IS-IS inter area, * - candidate default, U - per-user static route
      o - ODR, P - periodic downloaded static route, + - replicated route
Gateway of last resort is not set

10.0.0.0/24 is subnetted, 1 subnets
B 10.2.2.0 [200/0] via 100.100.2.1, 03:49:23
23.0.0.0/8 is variably subnetted, 13 subnets, 4 masks
B 23.0.0.0/8 [200/0] via 0.0.0.0, 03:51:56, Null0
L 23.0.0.1/32 is directly connected, Vlan1
I L1 23.0.0.16/28 [115/20] via 23.0.0.50, FastEthernet0/0
I L1 23.0.0.32/28 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.48/30 is directly connected, FastEthernet0/0
C 23.0.0.49/32 is directly connected, FastEthernet0/1
I L1 23.0.0.52/30 [115/20] via 23.0.0.58, FastEthernet0/1
I L1 23.0.0.56/30 [115/20] via 23.0.0.58, FastEthernet0/1
I L1 23.0.0.57/32 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.255.1/32 is directly connected, Loopback0
I L1 23.0.255.2/32 [115/10] via 23.0.0.50, FastEthernet0/0
I L1 23.0.255.3/32 [115/10] via 23.0.0.58, FastEthernet0/1
56.0.0.0/30 is subnetted, 1 subnets
I L1 56.0.0.60 [115/10] via 23.0.0.58, FastEthernet0/1
78.0.0.0/28 is subnetted, 3 subnets
B 78.0.0.0 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.16 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.32 [200/0] via 100.100.2.1, 03:48:32
    100.0.0.30 is subnetted, 1 subnets
I L1 100.100.2.0 [115/10] via 23.0.0.58, FastEthernet0/1
BT-R002#

```

(c) Router 3 (BT-R003)

```

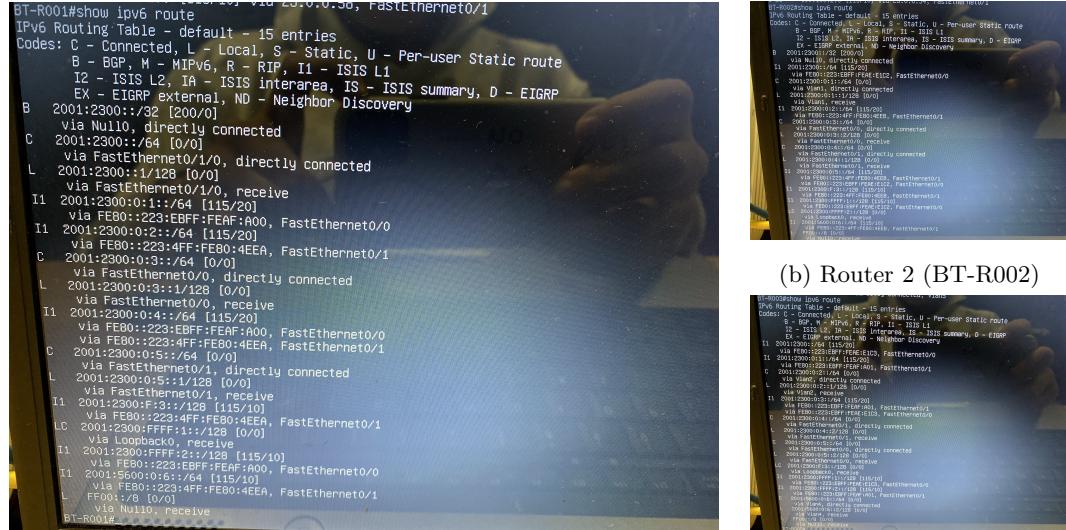
BT-R003#show ip route
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
      D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
      N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
      E1 - OSPF external type 1, E2 - OSPF external type 2
      L1 - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
      ia - IS-IS inter area, * - candidate default, U - per-user static route
      o - ODR, P - periodic downloaded static route, + - replicated route
Gateway of last resort is not set

10.0.0.0/24 is subnetted, 1 subnets
B 10.2.2.0 [200/0] via 100.100.2.1, 03:49:23
23.0.0.0/8 is variably subnetted, 13 subnets, 4 masks
B 23.0.0.0/8 [200/0] via 0.0.0.0, 03:50:06, Null0
L 23.0.0.1/32 is directly connected, Vlan1
I L1 23.0.0.16/28 [115/20] via 23.0.0.50, FastEthernet0/0
I L1 23.0.0.32/28 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.48/30 is directly connected, FastEthernet0/0
C 23.0.0.49/32 is directly connected, FastEthernet0/1
I L1 23.0.0.52/30 [115/20] via 23.0.0.58, FastEthernet0/1
I L1 23.0.0.56/30 [115/20] via 23.0.0.58, FastEthernet0/1
I L1 23.0.0.57/32 [115/20] via 23.0.0.58, FastEthernet0/1
C 23.0.0.255.1/32 is directly connected, Loopback0
I L1 23.0.255.2/32 [115/10] via 23.0.0.50, FastEthernet0/0
I L1 23.0.255.3/32 [115/10] via 23.0.0.58, FastEthernet0/1
56.0.0.0/30 is subnetted, 1 subnets
I L1 56.0.0.60 [115/10] via 23.0.0.58, FastEthernet0/1
78.0.0.0/28 is subnetted, 3 subnets
B 78.0.0.0 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.16 [200/0] via 100.100.2.1, 03:48:32
B 78.0.0.32 [200/0] via 100.100.2.1, 03:48:32
    100.0.0.30 is subnetted, 1 subnets
I L1 100.100.2.0 [115/10] via 23.0.0.58, FastEthernet0/1
BT-R003#

```

Figure 3.6: IPv4 Routes to Other Subnets on All 3 Routers Respectively using `show ip route`.

CHAPTER 3. ROUTING PROTOCOLS IN THE NETWORK



(a) Router 1 (BT-R001)

```

BT-R001#show ipv6 route
IPv6 Routing Table - default - 15 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
      B - BGP, M - MIPv6, R - RIP, I1 - ISIS L1
      I2 - ISIS L2, IA - ISIS interarea, IS - ISIS summary, D - EIGRP
      EX - EIGRP external, ND - Neighbor Discovery
B  2001:2300::/32 [200/0]
  via Null0, directly connected
C  2001:2300::/64 [0/0]
  via FastEthernet0/1, directly connected
L  2001:2300::1/128 [0/0]
  via FastEthernet0/1/0, receive
I1  2001:2300:0:1::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
I1  2001:2300:0:2::64 [115/20]
  via FE80::223:FF:FE80:4EEA, FastEthernet0/1
C  2001:2300:0:3::64 [0/0]
  via FastEthernet0/0, directly connected
L  2001:2300:0:3::1/128 [0/0]
  via FastEthernet0/0, receive
I1  2001:2300:0:4::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
C  2001:2300:0:5::64 [0/0]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  2001:2300:0:5::1/128 [0/0]
  via FastEthernet0/0, directly connected
I1  2001:2300:0:f3::1/128 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1  2001:2300:0:FFF1::1/128 [0/0]
  via loopback0, receive
I1  2001:2300:0:12::1/15/10
  via FE80::223:EBFF:FEAF:F000, FastEthernet0/0
I1  2001:5600:0:6::64 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  FF00::/8 [0/0]
  via Null0, receive
BT-R001#

```

(b) Router 2 (BT-R002)

```

BT-R002#show ipv6 route
IPv6 Routing Table - default - 15 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
      B - BGP, M - MIPv6, R - RIP, I1 - ISIS L1
      I2 - ISIS L2, IA - ISIS interarea, IS - ISIS summary, D - EIGRP
      EX - EIGRP external, ND - Neighbor Discovery
B  2001:2300::/32 [200/0]
  via Null0, directly connected
C  2001:2300::/64 [0/0]
  via FastEthernet0/1, directly connected
L  2001:2300::1/128 [0/0]
  via FastEthernet0/1/0, receive
I1  2001:2300:0:1::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
I1  2001:2300:0:2::64 [115/20]
  via FE80::223:FF:FE80:4EEA, FastEthernet0/1
C  2001:2300:0:3::64 [0/0]
  via FastEthernet0/0, directly connected
L  2001:2300:0:3::1/128 [0/0]
  via FastEthernet0/0, receive
I1  2001:2300:0:4::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
C  2001:2300:0:5::64 [0/0]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  2001:2300:0:5::1/128 [0/0]
  via FastEthernet0/0, directly connected
I1  2001:2300:0:f3::1/128 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1  2001:2300:0:FFF1::1/128 [0/0]
  via loopback0, receive
I1  2001:2300:0:12::1/15/10
  via FE80::223:EBFF:FEAF:F000, FastEthernet0/0
I1  2001:5600:0:6::64 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  FF00::/8 [0/0]
  via Null0, receive
BT-R002#

```

(c) Router 3 (BT-R003)

```

BT-R003#show ipv6 route
IPv6 Routing Table - default - 15 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
      B - BGP, M - MIPv6, R - RIP, I1 - ISIS L1
      I2 - ISIS L2, IA - ISIS interarea, IS - ISIS summary, D - EIGRP
      EX - EIGRP external, ND - Neighbor Discovery
B  2001:2300::/32 [200/0]
  via Null0, directly connected
C  2001:2300::/64 [0/0]
  via FastEthernet0/1, directly connected
L  2001:2300::1/128 [0/0]
  via FastEthernet0/1/0, receive
I1  2001:2300:0:1::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
I1  2001:2300:0:2::64 [115/20]
  via FE80::223:FF:FE80:4EEA, FastEthernet0/1
C  2001:2300:0:3::64 [0/0]
  via FastEthernet0/0, directly connected
L  2001:2300:0:3::1/128 [0/0]
  via FastEthernet0/0, receive
I1  2001:2300:0:4::64 [115/20]
  via FE80::223:EBFF:FEAF:A00, FastEthernet0/0
C  2001:2300:0:5::64 [0/0]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  2001:2300:0:5::1/128 [0/0]
  via FastEthernet0/0, directly connected
I1  2001:2300:0:f3::1/128 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1  2001:2300:0:FFF1::1/128 [0/0]
  via loopback0, receive
I1  2001:2300:0:12::1/15/10
  via FE80::223:EBFF:FEAF:F000, FastEthernet0/0
I1  2001:5600:0:6::64 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  FF00::/8 [0/0]
  via Null0, receive
BT-R003#

```

Figure 3.7: IPv6 Routes to Other Subnets on All 3 Routers Respectively using `show ipv6 route`.

Noticably, when the physical connection between Router 1 and Router 2 is broken, the route from Router 1 to Router 2 goes through Router 3 instead, as evident in Figure 3.8.

3.1.5 Commentary

3.1.5.1 Problem: IS-IS Not Set Up for Laptop-Router Interface

When initially setting up IS-IS on the interfaces, only the interfaces between routers have been turned on. This leads to laptop's failure to reach a router not directly connected. To solve this problem, IS-IS is set up on the interface between a laptop and a router.

3.1.5.2 Alternative Solution to Passive Interfaces

While turning interfaces connected to outside network into passive interfaces does enable other routers in the network to connect to outside networks through those interfaces, it demands extra computing resource for computing routes to external subnets.

Alternatively, one can disable IS-IS on such interfaces and replace the external next-hop for each out-going route in BGP with the internal router to which the next-hop is directly connected to. That prevents Router-Neighbour subnet from participating in IS-IS routing and eliminates the extra computing consumption while preserving the connectivity between internal routers and outside networks.

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```

Success rate is 80 percent (4/5), round-trip min/avg/max = 1/2/4 ms
BT-R001#sh ip route
Codes: L - local, C - connected, S - static, R - RIP, M - mobile, B - BGP
      D - EIGRP, EX - EIGRP external, O - OSPF, IA - OSPF inter area
      N1 - OSPF NSSA external type 1, N2 - OSPF NSSA external type 2
      E1 - OSPF external type 1, E2 - OSPF external type 2
      i - IS-IS, su - IS-IS summary, L1 - IS-IS level-1, L2 - IS-IS level-2
      ia - IS-IS inter area, * - candidate default, U - per-user static route
      o - ODR, P - periodic downloaded static route, + - replicated route
Gateway of last resort is not set

      10.0.0.0/24 is subnetted, 1 subnets
B        10.2.2.0 [200/0] via 100.100.2.1, 04:04:39
      23.0.0.0/8 is variably subnetted, 12 subnets, 4 masks
B          23.0.0.0/8 [200/0] via 0.0.0.0, 04:11:03, Null0
C          23.0.0.0/28 is directly connected, FastEthernet0/1/0
L          23.0.0.1/32 is directly connected, FastEthernet0/1/0
i L1        23.0.0.16/28 [115/30] via 23.0.0.58, FastEthernet0/1
i L1        23.0.0.32/28 [115/20] via 23.0.0.58, FastEthernet0/1
i L1        23.0.0.48/30 [115/30] via 23.0.0.58, FastEthernet0/1
i L1        23.0.0.52/30 [115/20] via 23.0.0.58, FastEthernet0/1
C          23.0.0.56/30 is directly connected, FastEthernet0/1
L          23.0.0.57/32 is directly connected, FastEthernet0/1
C          23.0.255.1/32 is directly connected, Loopback0
i L1        23.0.255.2/32 [115/20] via 23.0.0.58, FastEthernet0/1
i L1        23.0.255.3/32 [115/10] via 23.0.0.58, FastEthernet0/1
i L1        56.0.0.0/30 is subnetted, 1 subnets
i L1          56.0.0.60 [115/10] via 23.0.0.58, FastEthernet0/1
      78.0.0.0/28 is subnetted, 3 subnets
B          78.0.0.0 [200/0] via 100.100.2.1, 04:04:39
B          78.0.0.16 [200/0] via 100.100.2.1, 04:04:39
B          78.0.0.32 [200/0] via 100.100.2.1, 04:04:39
i L1        100.0.0.0/30 is subnetted, 1 subnets
i L1          100.100.2.0 [115/10] via 23.0.0.58, FastEthernet0/1
BT-R001#

```

(a) IPv4 Routes to Other Subnets on Router 1 using show ip route.

```

i L1        100.100.2.0 [115/10] via 23.0.0.58, FastEthernet0/1
BT-R001#sh ipv6 route
IPv6 Routing Table - default - 13 entries
Codes: C - Connected, L - Local, S - Static, U - Per-user Static route
      B - BGP, M - MIPv6, R - RIP, I1 - ISIS L1
      I2 - ISIS L2, IA - ISIS interarea, IS - ISIS summary, D - EIGRP
      EX - EIGRP external, ND - Neighbor Discovery
B  2001:2300::/32 [200/0]
  via Null0, directly connected
C  2001:2300::/64 [0/0]
  via FastEthernet0/1/0, directly connected
L  2001:2300::1/128 [0/0]
  via FastEthernet0/1/0, receive
I1 2001:2300:0:1::/64 [115/30]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1 2001:2300:0:2::/64 [115/20]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1 2001:2300:0:4::/64 [115/20]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
C  2001:2300:0:5::/64 [0/0]
  via FastEthernet0/1, directly connected
L  2001:2300:0:5::1/128 [0/0]
  via FastEthernet0/1, receive
I1 2001:2300:F:3::/128 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
LC 2001:2300:FFFF:1::128 [0/0]
  via Loopback0, receive
I1 2001:2300:FFFF:2::/128 [115/20]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
I1 2001:5600:0:6::/64 [115/10]
  via FE80::223:4FF:FE80:4EEA, FastEthernet0/1
L  FF00::/8 [0/0]
  via Null0, receive
BT-R001#

```

(b) IPv6 Routes to Other Subnets on Router 1 using show ip route.

Figure 3.8: IP Routes to Other Subnets on Router 1 when Physical Connection between Router 1 (BT-R001) and Router 2 (BT-R002) is broken.

3.2 Inter-domain Routing Protocol: BGP

3.2.1 Design

For inter-domain routing, Border Gateway Protocol (BGP)[6] is applied in BT Network since it's the one and only External Gateway Protocol (EGP) in today's global Internet. BGP provides scalability to large networks, clear definitions of administrative boundary as well as flexible policy control, which allow business relationships with neighbouring ISPs to be expressed in terms of routing policies.

Figure 3.9 shows the design of BGP protocol in our network. The AS Number (ASN) of BT Network is 2030 while ASN of Central, Virgin, DT are 42, 5060, 3040 respectively.

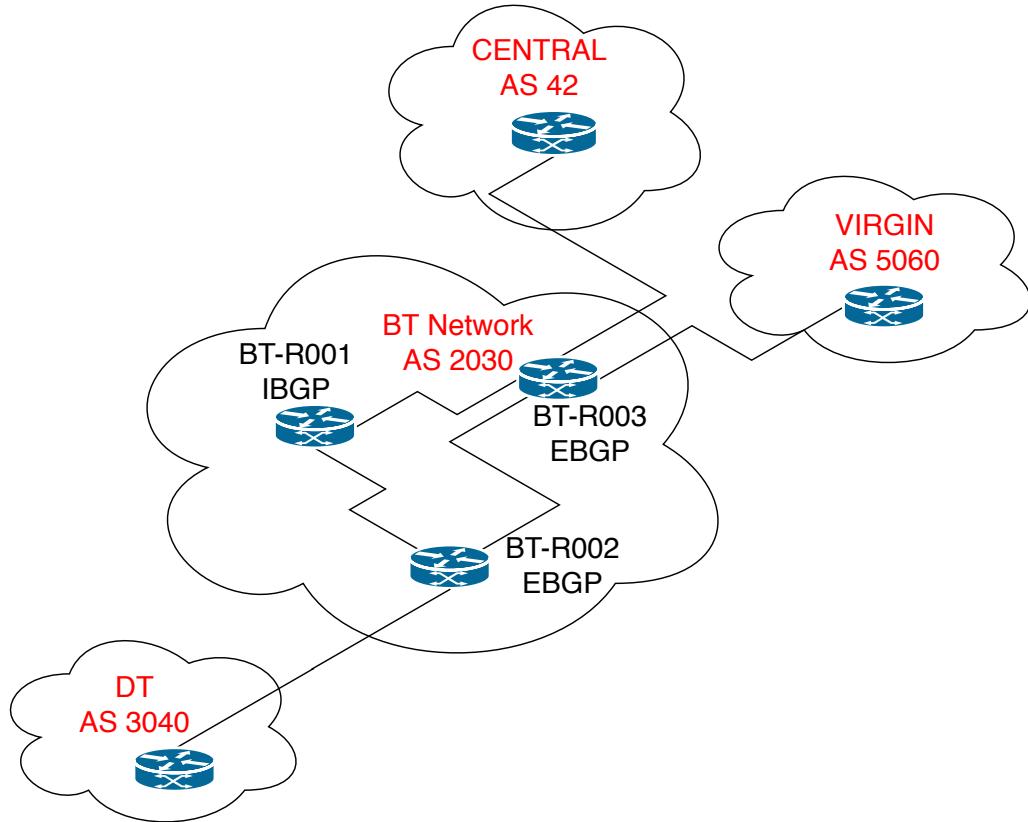


Figure 3.9: Design of BGP Protocol in BT Network.

Router 2 (BT-R002) and Router 3 (BT-R003) act as External BGP routers since they are directly connected to neighbouring ISPs. They receive routes announced by neighbouring ISPs' routers and announce routes originated from BT Network. Router 1 (BT-R001) acts

as an Internal BGP (IBGP) router only since it is not directly connected to any neighbouring ISP and only forwards and receives routes announced by EGBP routers.

3.2.2 Routing Policies

To enact business relationships with neighbouring ISPs, proper routing policies should be implemented for each different relationship in BGP protocol. Specifically, for customer ISPs, all routes announced by such ISP should be accepted and all routes received should be announced to it as well. This allows customers to connect to BT Network as well as connect to other networks through BT Network.

For non-customer neighbouring ISPs (peers and providers), all routes announced by such ISP should be accepted in order for BT Network to connect to it. Meanwhile, only routes originated from either BT Network or BT's customers are announced to such ISP.

3.2.3 Implementation

On Router 1 (BT-R001, IPv4 Loopback Address: 23.0.255.1, IPv6 Loopback Address: 2001:2300:FFFF:1::), both Router 2 (BT-R002, IPv4 Loopback Address: 23.0.255.2, IPv6 Loopback Address: 2001:2300:FFFF:2::) and Router 3 (BT-R003, IPv4 Loopback Address: 23.0.255.3, IPv6 Loopback Address: 2001:2300:FFFF:3::) are taken as neighbouring routers in the same AS. In addition, the source of BGP messages are set to be the loopback address of Router 1 to prevent physical disconnection to the 2 routers. Router 1 announces the subnet BT-R001 – BT001 (IPv4: 23.0.0.0/28, IPv6: 2001:2300:0:0::/64) to other routers.

```
1 router bgp 2030
2 network 23.0.0.0 mask 255.255.255.240
3 neighbor 23.0.255.2 remote-as 2030
4 neighbor 23.0.255.2 update-source Loopback0
5 neighbor 23.0.255.3 remote-as 2030
6 neighbor 23.0.255.3 update-source Loopback0
7 neighbor 2001:2300:FFFF:2:: remote-as 2030
8 neighbor 2001:2300:FFFF:2:: update-source Loopback0
9 neighbor 2001:2300:FFFF:3:: remote-as 2030
10 neighbor 2001:2300:FFFF:3:: update-source Loopback0
11
12 address-family ipv6
13 network 2001:2300::/64
14 neighbor 2001:2300:FFFF:2:: activate
15 neighbor 2001:2300:FFFF:3:: activate
```

On Router 2 (BT-R002), both Router 1 and Router 3 are taken as neighbouring routers in the same AS while the router from DT is taken as router from AS 3040. Router 2 announces

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the subnet BT-R002 – BT002 (IPv4: 23.0.0.16/28, IPv6: 2001:2300:0:1::/64) to other routers. Since Router 2 is directly connected to customer DT Network, it applies no filter on inbound and outbound routes.

```
1 router bgp 2030
2 network 23.0.0.16 mask 255.255.255.240
3 neighbor 23.0.0.62 remote-as 3040
4 neighbor 23.0.255.1 remote-as 2030
5 neighbor 23.0.255.1 update-source Loopback0
6 neighbor 23.0.255.3 remote-as 2030
7 neighbor 23.0.255.3 update-source Loopback0
8 neighbor 2001:2300:0:6::2 remote-as 3040
9 neighbor 2001:2300:FFFF:1:: remote-as 2030
10 neighbor 2001:2300:FFFF:1:: update-source Loopback0
11 neighbor 2001:2300:FFFF:3:: remote-as 2030
12 neighbor 2001:2300:FFFF:3:: update-source Loopback0
13
14 address-family ipv6
15 network 2001:2300:0:1::/64
16 neighbor 2001:2300:0:6::2 activate
17 neighbor 2001:2300:FFFF:1:: activate
18 neighbor 2001:2300:FFFF:3:: activate
```

On Router 3 (BT-R003), both Router 1 and Router 2 are taken as neighbouring routers in the same AS while the routers from Central and Virgin are taken as router from AS 42 and AS 5060 respectively. Router 3 announces the subnet BT-R003 – BT003 (IPv4: 23.0.0.32/28, IPv6: 2001:2300:0:2::/64) to other routers.

```
1 router bgp 2030
2 network 23.0.0.32 mask 255.255.255.240
3 neighbor 23.0.255.1 remote-as 2030
4 neighbor 23.0.255.1 update-source Loopback0
5 neighbor 23.0.255.2 remote-as 2030
6 neighbor 23.0.255.2 update-source Loopback0
7 neighbor 2001:2300:FFFF:1:: remote-as 2030
8 neighbor 2001:2300:FFFF:1:: update-source Loopback0
9 neighbor 2001:2300:FFFF:2:: remote-as 2030
10 neighbor 2001:2300:FFFF:2:: update-source Loopback0
11 neighbor 2001:5600:0:6::1 remote-as 5060
12 neighbor 56.0.0.61 remote-as 5060
13 neighbor 100.100.2.1 remote-as 42
14
15 address-family ipv6
16 network 2001:2300:0:2::/64
17 aggregate-address 2001:2300::/32 summary-only
18 neighbor 2001:2300:FFFF:1:: activate
19 neighbor 2001:2300:FFFF:2:: activate
```

Since Router 3 is directly connected to non-customer ISPs, it applies a filter on outbound routes, which denies all routes that pass through either Central Network (ASN: 42) or Virgin Network (ASN: 5060).

```
1 ip as-path access-list 1 deny _42_
2 ip as-path access-list 1 deny _5060_
3 ip as-path access-list 1 permit .*
4 router bgp 2030
5 neighbor 56.0.0.61 filter-list 1 out
6 neighbor 100.100.2.1 filter-list 1 out
```

Address aggregation for 23.0.0.0/8 and 2001:2300::/32 is set up on all 3 routers, which aggregates routes destined for all addresses inside BT Network range into a single route.

```
1 aggregate-address 23.0.0.0 255.0.0.0 summary-only
2 address-family ipv6
3 aggregate-address 2001:2300::/32 summary-only
```

3.2.4 Evaluation

3.2.4.1 BGP Routes

Routes collected through BGP protocol on all 3 routers are shown in Figure 3.10 and ?? using commands `show bgp` and `show bgp ipv6`. Routes to DT Network (IPv4: 34.0.0.0/8, IPv6: 2001:3400::/32), Virgin Network (IPv4: 56.0.0.0/8, IPv6: 2001:5600::/32), Central Network (IPv4: 10.2.2.0/24) and other networks can be observed in the figure.

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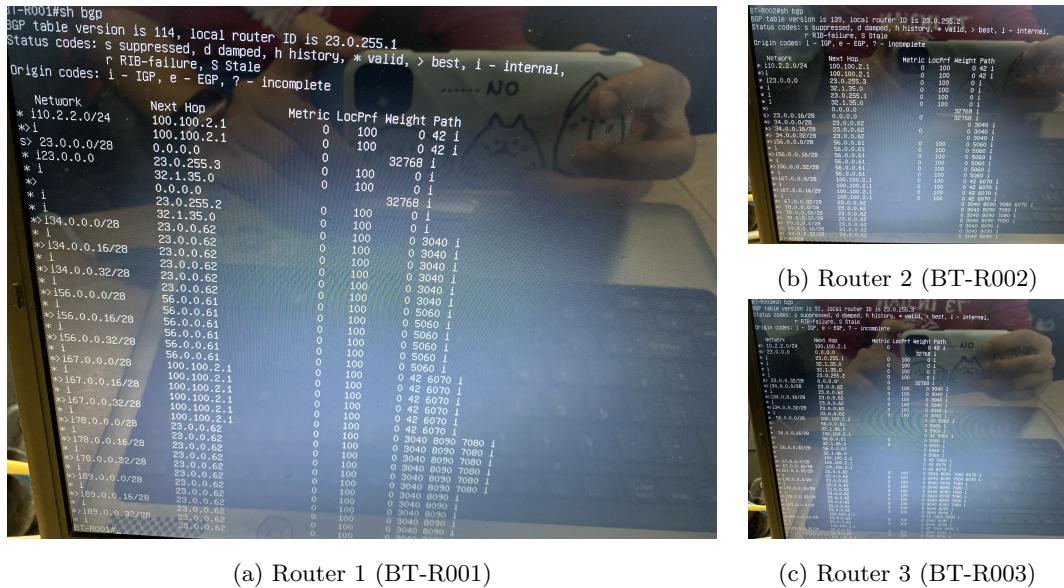
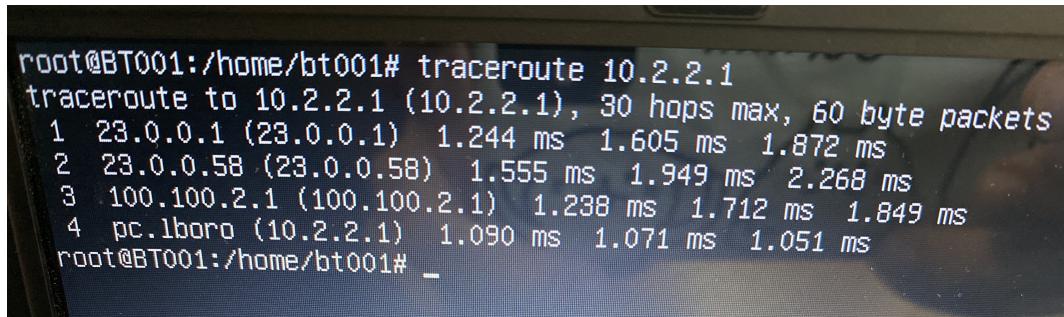


Figure 3.10: IPv4 Routes Collected through BGP Protocols on All 3 Routers using `show bgp`

3.2.4.2 Connectivity to Provider Central Network

The connectivity to provider Central Network using BGP protocol is tested and evaluated by tracing routes to IP addresses 10.2.2.1 on Laptop 1 (BT001). As shown in Figure 3.11, connection to Central Network is successfully established through BGP routes.

A screenshot of a terminal window on a laptop screen. The terminal is running on root privilege (root@BT001) and executing the command 'traceroute 10.2.2.1'. The output shows the path taken by the packets to reach the destination. The first four lines of the output are:

```
root@BT001:/home/bt001# traceroute 10.2.2.1
traceroute to 10.2.2.1 (10.2.2.1), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.244 ms  1.605 ms  1.872 ms
 2  23.0.0.58 (23.0.0.58)  1.555 ms  1.949 ms  2.268 ms
 3  100.100.2.1 (100.100.2.1)  1.238 ms  1.712 ms  1.849 ms
 4  pc.lboro (10.2.2.1)  1.090 ms  1.071 ms  1.051 ms
```

(a) 10.2.2.1

Figure 3.11: Tracing IPv4 Routes to Central Network on Laptop 1 (BT001) using **traceroute**.

3.2.4.3 Connectivity to Customer DT Network

The connectivity to customer DT Network using BGP protocol is tested and evaluated by tracing routes to IP addresses 34.0.0.2, 34.0.0.18 and 34.0.0.34 on Laptop 1 (BT001). As shown in Figure 3.12, connection to DT Network is successfully established through BGP routes.

(a) 34.0.0.2

```
root@BT001:/home/bt001# traceroute 34.0.0.2
traceroute to 34.0.0.2 (34.0.0.2), 30 hops max, 60 byte packets
1 23.0.0.1 (23.0.0.1) 1.225 ms 1.424 ms 1.736 ms
2 23.0.0.50 (23.0.0.50) 1.377 ms 1.668 ms 2.059 ms
3 23.0.0.62 (23.0.0.62) 1.779 ms 2.294 ms 2.740 ms
4 34.0.0.53 (34.0.0.53) 1.963 ms 2.218 ms 2.627 ms
5 34.0.0.2 (34.0.0.2) 1.631 ms 1.612 ms 2.556 ms
root@BT001:/home/bt001#
```

(b) 34.0.0.18

```
root@BT001:/home/bt001# traceroute 34.0.0.18
traceroute to 34.0.0.18 (34.0.0.18), 30 hops max, 60 byte packets
1 23.0.0.1 (23.0.0.1) 1.245 ms 1.441 ms 1.861 ms
2 23.0.0.50 (23.0.0.50) 1.406 ms 1.810 ms 2.216 ms
3 23.0.0.62 (23.0.0.62) 2.020 ms 2.367 ms 2.827 ms
4 34.0.0.18 (34.0.0.18) 1.536 ms 1.487 ms 1.467 ms
root@BT001:/home/bt001# ..... NO
```

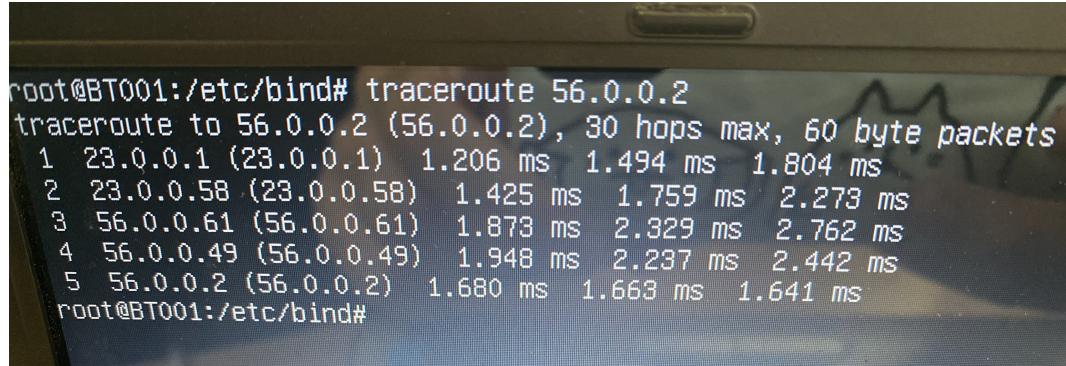
(c) 34.0.0.34

```
root@BT001:/home/bt001# traceroute 34.0.0.34
traceroute to 34.0.0.34 (34.0.0.34), 30 hops max, 60 byte packets
1 23.0.0.1 (23.0.0.1) 1.231 ms 1.424 ms 1.733 ms
2 23.0.0.50 (23.0.0.50) 1.376 ms 1.666 ms 2.049 ms
3 23.0.0.62 (23.0.0.62) 1.870 ms 2.317 ms 2.909 ms
4 34.0.0.57 (34.0.0.57) 2.109 ms 2.333 ms 2.652 ms
5 34.0.0.34 (34.0.0.34) 1.658 ms 1.642 ms 2.557 ms
root@BT001:/home/bt001# ..... NO
```

Figure 3.12: Tracing IPv4 Routes to DT Network on Laptop 1 (BT001) using `traceroute`.

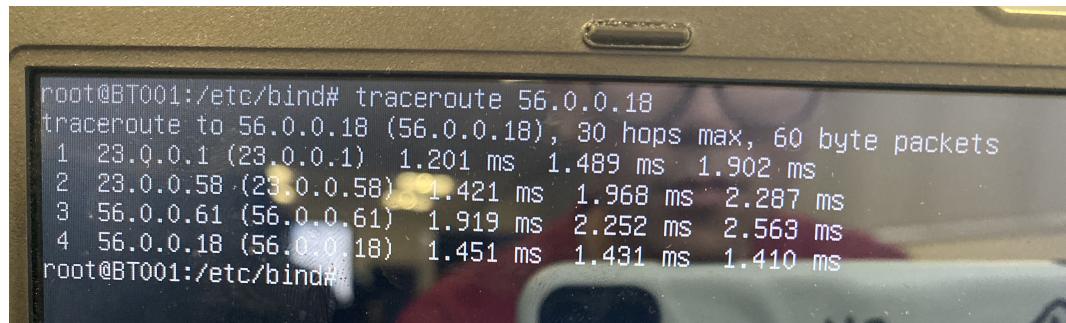
3.2.4.4 Connectivity to Peer Virgin Network

The connectivity to peer Virgin Network using BGP protocol is tested and evaluated by tracing routes to IP addresses 56.0.0.2, 56.0.0.18 and 56.0.0.34 on Laptop 1 (BT001). As shown in Figure 3.14, connection to Virgin Network is successfully established through BGP routes.



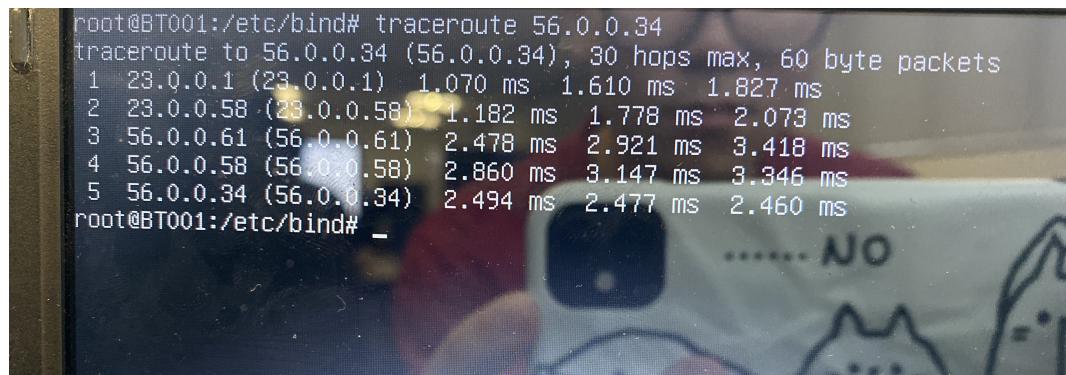
```
root@BT001:/etc/bind# traceroute 56.0.0.2
traceroute to 56.0.0.2 (56.0.0.2), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.206 ms  1.494 ms  1.804 ms
 2  23.0.0.58 (23.0.0.58)  1.425 ms  1.759 ms  2.273 ms
 3  56.0.0.61 (56.0.0.61)  1.873 ms  2.329 ms  2.762 ms
 4  56.0.0.49 (56.0.0.49)  1.948 ms  2.237 ms  2.442 ms
 5  56.0.0.2 (56.0.0.2)  1.680 ms  1.663 ms  1.641 ms
root@BT001:/etc/bind#
```

(a) 56.0.0.2



```
root@BT001:/etc/bind# traceroute 56.0.0.18
traceroute to 56.0.0.18 (56.0.0.18), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.201 ms  1.489 ms  1.902 ms
 2  23.0.0.58 (23.0.0.58)  1.421 ms  1.968 ms  2.287 ms
 3  56.0.0.61 (56.0.0.61)  1.919 ms  2.252 ms  2.563 ms
 4  56.0.0.18 (56.0.0.18)  1.451 ms  1.481 ms  1.410 ms
root@BT001:/etc/bind#
```

(b) 56.0.0.18



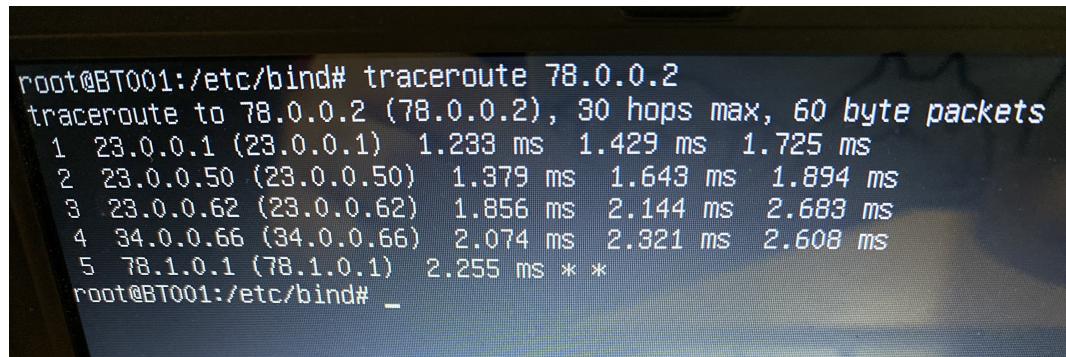
```
root@BT001:/etc/bind# traceroute 56.0.0.34
traceroute to 56.0.0.34 (56.0.0.34), 30 hops max, 60 byte packets
 1  23.0.0.1 (23.0.0.1)  1.070 ms  1.610 ms  1.827 ms
 2  23.0.0.58 (23.0.0.58)  1.182 ms  1.778 ms  2.073 ms
 3  56.0.0.61 (56.0.0.61)  2.478 ms  2.921 ms  3.418 ms
 4  56.0.0.58 (56.0.0.58)  2.860 ms  3.147 ms  3.346 ms
 5  56.0.0.34 (56.0.0.34)  2.494 ms  2.477 ms  2.460 ms
root@BT001:/etc/bind#
```

(c) 56.0.0.34

Figure 3.13: Tracing IPv4 Routes to Virgin Network on Laptop 1 (BT001) using traceroute.

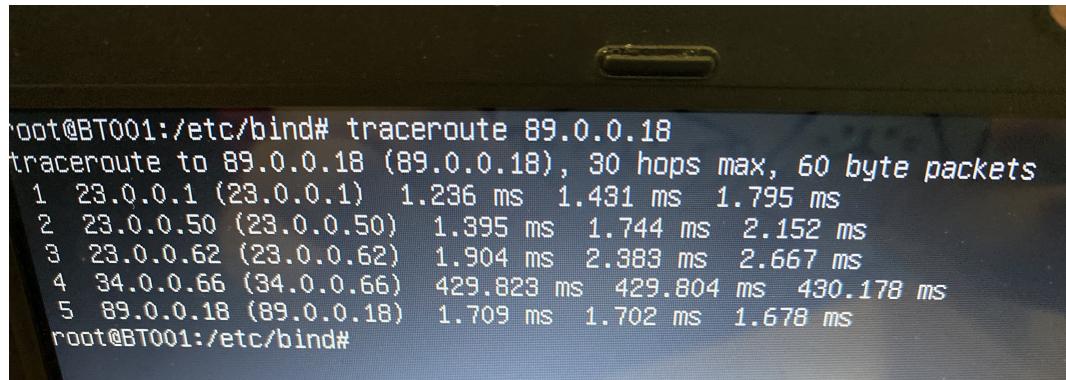
3.2.4.5 Connectivity to Other Networks

The connectivity to other networks using BGP protocol is tested and evaluated by tracing routes to IP addresses 78.0.0.2 (Sonara Network) and 89.0.0.18 (NTT Network) on Laptop 1 (BT001). As shown in Figure 3.14, connection to Virgin Network is successfully established through BGP routes.



```
root@BT001:/etc/bind# traceroute 78.0.0.2
traceroute to 78.0.0.2 (78.0.0.2), 30 hops max, 60 byte packets
 1 23.0.0.1 (23.0.0.1) 1.233 ms 1.429 ms 1.725 ms
 2 23.0.0.50 (23.0.0.50) 1.379 ms 1.643 ms 1.894 ms
 3 23.0.0.62 (23.0.0.62) 1.856 ms 2.144 ms 2.683 ms
 4 34.0.0.66 (34.0.0.66) 2.074 ms 2.321 ms 2.608 ms
 5 78.1.0.1 (78.1.0.1) 2.255 ms * *
root@BT001:/etc/bind# _
```

(a) 78.0.0.2



```
root@BT001:/etc/bind# traceroute 89.0.0.18
traceroute to 89.0.0.18 (89.0.0.18), 30 hops max, 60 byte packets
 1 23.0.0.1 (23.0.0.1) 1.236 ms 1.431 ms 1.795 ms
 2 23.0.0.50 (23.0.0.50) 1.395 ms 1.744 ms 2.152 ms
 3 23.0.0.62 (23.0.0.62) 1.904 ms 2.383 ms 2.667 ms
 4 34.0.0.66 (34.0.0.66) 429.823 ms 429.804 ms 430.178 ms
 5 89.0.0.18 (89.0.0.18) 1.709 ms 1.702 ms 1.678 ms
root@BT001:/etc/bind#
```

(b) 89.0.0.18

Figure 3.14: Tracing IPv4 Routes to Other Networks on Laptop 1 (BT001) using `traceroute`.

3.2.5 Commentary

3.2.5.1 Problem: Filter List Not Working for Self-Originated Routes

The initial filter list for outbound routes on Router 3 only permits routes originated from BT Network (ASN 2030) and customer DT Network (ASN 3040).

```
1 ip as-path access-list 1 permit _2030$  
2 ip as-path access-list 1 permit _3040$
```

However, the filter list blocks all routes except those originated from customer DT Network to be announced. To solve this problem, a filter list where all routes except those go through provider Central Network (ASN 42) and peer Virgin Network (ASN 5060) are allowed. The new list should have the same effects as the previous list and indeed works as intended.

```
1 ip as-path access-list 1 deny _42_  
2 ip as-path access-list 1 deny _5060_  
3 ip as-path access-list 1 permit ..*
```

Chapter 4

Applications in the Network

4.1 Secure Remote Access to Routers through SSH

4.1.1 Design

Accessing the routers through the physical "console" port is inconvenient and dangerous. Thus, remote access through Secure Shell (SSH) protocol[7] to routers is needed.

In BT network, remote SSH access is enabled on all 3 routers. Separate combinations of username and password on each router are used to ensure the independence of security of each router.

In addition, SSH public key authentication is set up on Laptop 1 (BT001), which allows the root user on the laptop to login in to all routers without entering passwords.

4.1.2 Implementation

We first set up Remote SSH access was first set up as instructed in Reference Guide on all 3 routers. Below is the configuration commands for Router 1 (BT-R001).

```

1 hostname BT-R001
2 ip domain name bt.lboro
3 username r001 priv 15 secret <secret>
4 line vty 0 4
5 transport input ssh telnet
6 login local
7
8 ip ssh version 2
9 crypto key generate rsa general-keys
10 ip ssh dh min size 4096

```

We then generate a pair of public and private keys on Laptop 1 (BT001).

```
1 ssh-keygen
```

After that, the pair of keys is written into files `~/.ssh/id_rsa` and `~/.ssh/id_rsa.pub`. We use the generated public key (`id_rsa.pub`) to set up SSH public key authentication on all 3 routers.

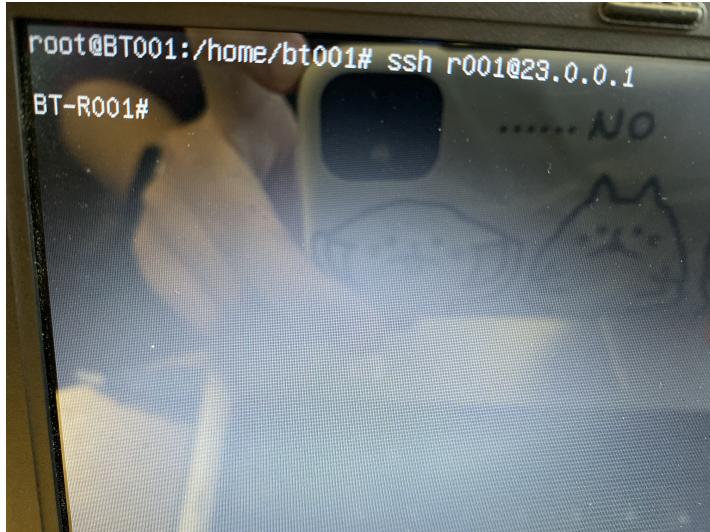
```
1 ip ssh pubkey-chain
2 username r001
3 key-string
```

4.1.3 Evaluation

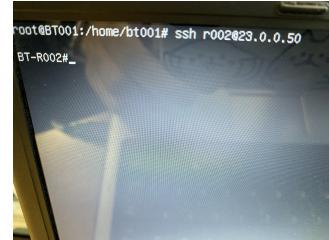
Once remote SSH access is set up on 3 routers, one should be able to access them on Laptop 1 (BT001) without entering the password using the following commands.

```
1 # access Router 1
2 ssh r001@23.0.0.1
3 # access Router 2
4 ssh r002@23.0.0.50
5 # access Router 3
6 ssh r003@23.0.0.33
```

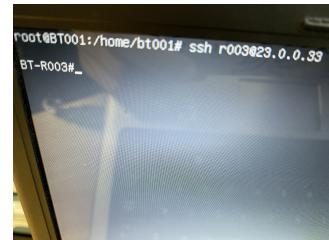
Screenshots of successful remote access to all 3 routers are shown in Figure 4.1.



(a) Router 1 (BT-R001)



(b) Router 2 (BT-R002)



(c) Router 3 (BT-R003)

Figure 4.1: Sucessful remote SSH access to all 3 routers from Laptop 1 (BT001).

4.1.4 Commentary

4.1.4.1 Problem: Maximum Limit of Characters per Line

When we tried to set up SSH public key authentication on routers, we failed at our initial attempt. It turned out that Cisco router has maximum limit of characters for each command line. Thus, a public key in a single long line was not accepted by the router.

To solve this problem, `fold` command is used to split the public key into multiple lines before re-uploading the key and SSH public key authentication was successfully set up on the router.

4.2 World Wide Web Service

4.2.1 Design

A World Wide Web (WWW) service[8][9] in the network allows any terminal devices to access the deployed webpages. The service is established after routers and three laptops have been configurated and DNS service been set up.

For this lab, `apache2` package is chosen as the tool to establish the web server on Laptop 1 (BT001). Using the default settings of this package is enough and it has a specific folder static web pages are stored.

4.2.2 Implementation

Install `apache2` package on Laptop 1 (BT001, IPv4 Address: 23.0.0.2) using following the command.

```
1 sudo apt-get install apache2
```

A HTML file named `index.html` is created as a test webpage, as detailed followed.

```
1 <html>
2 <header><title>BT Network</title></header>
3 <body>
4 <h1>Welcome to BT Network |</h1>
5 A Trustworthy Internet Service Provider at Loughborough University.
6 </body>
7 </html>
```

Figure 4.2: Contents of HTML File Named `index.html`

Then, the HTML file is copied to the folder `/var/www/html`. This folder is used to deploy webpages on the server. And the meaning of `-r` is to cover the same name file.

```
1 cp -r index.html /var/www/html
```

Then, install `links` package which is a command-line Web browser in Linux by using following command.

```
1 sudo apt-get install links
```

Then, `links` is started and the web page is accessed through URL with the local IP address.

```
1 links http://23.0.0.2/
```

Finally, add the following lines to the forward DNS file `/etc/bind/db.bt.lbورو` on Primary DNS Server at Laptop 3 (BT003). This enables the clients to browse the webpages by domain name `bt.lbورو`.

```
1 @ IN A 23.0.0.2  
2 @ IN AAAA 2001:2300:0:0::2
```

4.2.3 Evaluation

The web service is tested using the following command on Laptop 2, which is neither a DNS Server nor a Web Server.

```
1 links http://bt.lbورو/
```

As shown in Figure 4.3, the service has been successfully set up and is accessible in the network.

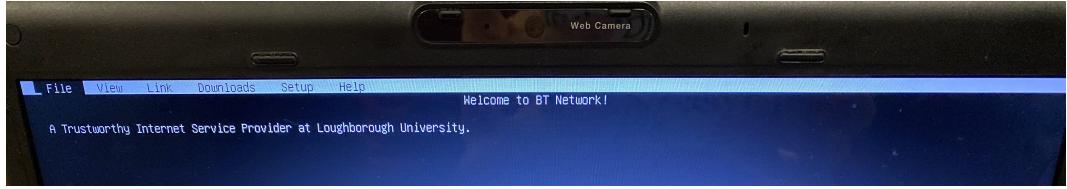


Figure 4.3: Web Service Provided at `http://bt.lbورو` .

4.3 Domain Name System Service

4.3.1 Design

4.3.2 Implementation

4.3.3 Evaluation

4.3.4 Commentary

4.4 Email Service

4.4.1 Design

4.4.2 Implementation

4.4.3 Evaluation

4.4.4 Commentary

Chapter 5

Discussion

5.1 Conclusions

5.2 Further Work

Chapter 6

Contributions

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6.3 Network Engineer: Huijing LEI

6.4 Network Engineer: Changrong CHEN

6.5 Network Engineer: Yan HUANG

REFERENCES

References

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- [2] Bob Hinden and Dr. Steve E. Deering. Internet Protocol, Version 6 (IPv6) Specification. RFC 2460, December 1998.
- [3] Gary S. Malkin. RIP Version 2. RFC 2453, November 1998.
- [4] OSI IS-IS Intra-domain Routing Protocol. RFC 1142, February 1990.
- [5] John Moy. OSPF Version 2. RFC 2328, April 1998.
- [6] Yakov Rekhter, Susan Hares, and Tony Li. A Border Gateway Protocol 4 (BGP-4). RFC 4271, January 2006.
- [7] Chris M. Lonvick and Tatu Ylonen. The Secure Shell (SSH) Transport Layer Protocol. RFC 4253, January 2006.
- [8] Tim Berners-Lee. Universal Resource Identifiers in WWW: A Unifying Syntax for the Expression of Names and Addresses of Objects on the Network as used in the World-Wide Web. RFC 1630, June 1994.
- [9] Henrik Frystyk Nielsen, Jeffrey Mogul, Larry M Masinter, Roy T. Fielding, Jim Gettys, Paul J. Leach, and Tim Berners-Lee. Hypertext Transfer Protocol – HTTP/1.1. RFC 2616, June 1999.

Appendix A

Routers Configuration

A.1 Router 1 Configuration

```

1
2 !
3 ! Last configuration change at 14:43:27 UTC Mon Nov 4 2019 by r001
4 !
5 version 15.0
6 service timestamps debug datetime msec
7 service timestamps log datetime msec
8 no service password-encryption
9 !
10 hostname BT-R001
11 !
12 boot-start-marker
13 boot-end-marker
14 !
15 !
16 no aaa new-model
17 dot11 syslog
18 ip source-route
19 !
20 !
21 !
22 !
23 ip cef
24 no ip domain lookup
25 ip domain name bt.llboro
26 ipv6 unicast-routing
27 ipv6 cef

```

APPENDIX A. ROUTERS CONFIGURATION

```
28 multilink bundle-name authenticated
29 !
30 !
31 !
32 !
33 !
34 !
35 !
36 !
37 !
38 voice-card 0
39 !
40 !
41 !
42 !
43 !
44 license udi pid CISCO2801 sn FCZ1339C10B
45 username r001 privilege 15 secret 5 $1$zzE2$UaRCPrx0iQCcbQ1Jg1Ys21
46 !
47 !
48 ip ssh version 2
49 ip ssh dh min size 4096
50 ip ssh pubkey-chain
51 username r001
52 key-hash ssh-rsa AFC27BDF03A4FB6173D4D0482B4C084A
53 key-hash ssh-rsa 601E98BF47BA6CC0089AEC1177F6DEE5 root@BT001
54 !
55 !
56 !
57 !
58 !
59 interface Loopback0
60 ip address 23.0.255.1 255.255.255.255
61 ipv6 address 2001:2300:FFFF:1::/128
62 !
63 interface FastEthernet0/0
64 ip address 23.0.0.49 255.255.255.252
65 ip router isis
66 duplex auto
67 speed auto
68 ipv6 address 2001:2300:0:3::1/64
69 ipv6 router isis
70 !
71 interface FastEthernet0/1
72 ip address 23.0.0.57 255.255.255.252
73 ip router isis
74 duplex auto
```

APPENDIX A. ROUTERS CONFIGURATION

```
75 speed auto
76 ipv6 address 2001:2300:0:5::1/64
77 ipv6 router isis
78 !
79 interface FastEthernet0/1/0
80 ip address 23.0.0.1 255.255.255.240
81 ip router isis
82 duplex auto
83 speed auto
84 ipv6 address 2001:2300::1/64
85 ipv6 router isis
86 !
87 router isis
88 net 49.0001.0230.0025.5001.00
89 is-type level-1
90 passive-interface Loopback0
91 !
92 router bgp 2030
93 no synchronization
94 bgp log-neighbor-changes
95 network 23.0.0.0 mask 255.255.255.240
96 aggregate-address 23.0.0.0 255.0.0.0 summary-only
97 neighbor 23.0.255.2 remote-as 2030
98 neighbor 23.0.255.2 update-source Loopback0
99 neighbor 23.0.255.3 remote-as 2030
100 neighbor 23.0.255.3 update-source Loopback0
101 neighbor 2001:2300:FFFF:2:: remote-as 2030
102 neighbor 2001:2300:FFFF:2:: update-source Loopback0
103 neighbor 2001:2300:FFFF:3:: remote-as 2030
104 neighbor 2001:2300:FFFF:3:: update-source Loopback0
105 no auto-summary
106 !
107 address-family ipv6
108 network 2001:2300::/64
109 aggregate-address 2001:2300::/32 summary-only
110 neighbor 2001:2300:FFFF:2:: activate
111 neighbor 2001:2300:FFFF:3:: activate
112 exit-address-family
113 !
114 ip forward-protocol nd
115 !
116 !
117 no ip http server
118 no ip http secure-server
119 !
120 !
121 !
```

APPENDIX A. ROUTERS CONFIGURATION

```
122 !
123 control-plane
124 !
125 !
126 !
127 mgcp fax t38 ecm
128 mgcp behavior g729-variants static-pt
129 !
130 !
131 !
132 !
133 line con 0
134 line aux 0
135 line vty 0 4
136 login local
137 transport input telnet ssh
138 !
139 scheduler allocate 20000 1000
140 end
```

A.2 Router 2 Configuration

```
1 !
2 !
3 ! Last configuration change at 14:35:53 UTC Mon Nov 4 2019 by r002
4 !
5 version 15.0
6 service timestamps debug datetime msec
7 service timestamps log datetime msec
8 no service password-encryption
9 !
10 hostname BT-R002
11 !
12 boot-start-marker
13 boot-end-marker
14 !
15 !
16 no aaa new-model
17 dot11 syslog
18 ip source-route
19 !
20 !
21 !
22 !
23 ip cef
24 no ip domain lookup
25 ip domain name bt.lboro
26 ipv6 unicast-routing
27 ipv6 cef
28 multilink bundle-name authenticated
29 !
30 !
31 !
32 !
33 !
34 !
35 !
36 !
37 !
38 voice-card 0
39 !
40 !
41 !
42 !
43 !
44 license udi pid CISCO2801 sn FCZ1339C100
```

APPENDIX A. ROUTERS CONFIGURATION

```
45 username r002 privilege 15 secret 5 $1$..EF$yfYESFK6llTyMnP.f1ABh0
46 !
47 !
48 ip ssh version 2
49 ip ssh dh min size 4096
50 ip ssh pubkey-chain
51 username r002
52     key-hash ssh-rsa 601E98BF47BA6CC0089AEC1177F6DEE5 root@BT001
53 !
54 !
55 !
56 !
57 !
58 interface Loopback0
59     ip address 23.0.255.2 255.255.255.255
60     ipv6 address 2001:2300:FFFF:2::/128
61 !
62 interface FastEthernet0/0
63     ip address 23.0.0.50 255.255.255.252
64     ip router isis
65     duplex auto
66     speed auto
67     ipv6 address 2001:2300:0:3::2/64
68     ipv6 router isis
69 !
70 interface FastEthernet0/1
71     ip address 23.0.0.53 255.255.255.252
72     ip router isis
73     duplex auto
74     speed auto
75     ipv6 address 2001:2300:0:4::1/64
76     ipv6 router isis
77 !
78 interface FastEthernet0/1/0
79 !
80 interface FastEthernet0/1/1
81     switchport access vlan 3
82 !
83 interface FastEthernet0/1/2
84 !
85 interface FastEthernet0/1/3
86 !
87 interface Vlan1
88     ip address 23.0.0.17 255.255.255.240
89     ip router isis
90     ipv6 address 2001:2300:0:1::1/64
91     ipv6 router isis
```

APPENDIX A. ROUTERS CONFIGURATION

```
92 !
93 interface Vlan3
94 ip address 23.0.0.61 255.255.255.252
95 ipv6 address 2001:2300:0:6::1/64
96 !
97 router isis
98 net 49.0001.0230.0025.5002.00
99 is-type level-1
100 passive-interface Vlan3
101 passive-interface Loopback0
102 !
103 router bgp 2030
104 bgp log-neighbor-changes
105 neighbor 23.0.0.62 remote-as 3040
106 neighbor 23.0.255.1 remote-as 2030
107 neighbor 23.0.255.1 update-source Loopback0
108 neighbor 23.0.255.3 remote-as 2030
109 neighbor 23.0.255.3 update-source Loopback0
110 neighbor 2001:2300:0:6::2 remote-as 3040
111 neighbor 2001:2300:FFFF:1:: remote-as 2030
112 neighbor 2001:2300:FFFF:1:: update-source Loopback0
113 neighbor 2001:2300:FFFF:3:: remote-as 2030
114 neighbor 2001:2300:FFFF:3:: update-source Loopback0
115 !
116 address-family ipv4
117 no synchronization
118 network 23.0.0.16 mask 255.255.255.240
119 aggregate-address 23.0.0.0 255.0.0.0 summary-only
120 neighbor 23.0.0.62 activate
121 neighbor 23.0.255.1 activate
122 neighbor 23.0.255.3 activate
123 neighbor 2001:2300:0:6::2 activate
124 neighbor 2001:2300:FFFF:1:: activate
125 neighbor 2001:2300:FFFF:3:: activate
126 no auto-summary
127 exit-address-family
128 !
129 address-family ipv6
130 network 2001:2300:0:1::/64
131 aggregate-address 2001:2300::/32 summary-only
132 neighbor 2001:2300:0:6::2 activate
133 neighbor 2001:2300:FFFF:1:: activate
134 neighbor 2001:2300:FFFF:3:: activate
135 exit-address-family
136 !
137 ip forward-protocol nd
138 !
```

APPENDIX A. ROUTERS CONFIGURATION

```
139 !
140 no ip http server
141 no ip http secure-server
142 !
143 !
144 !
145 !
146 control-plane
147 !
148 !
149 !
150 mgcp fax t38 ecm
151 mgcp behavior g729-variants static-pt
152 !
153 !
154 !
155 !
156 line con 0
157 line aux 0
158 line vty 0 4
159 login local
160 transport input telnet ssh
161 !
162 scheduler allocate 20000 1000
163 end
```

A.3 Router 3 Configuration

```
1 !
2 !
3 ! Last configuration change at 06:40:58 UTC Sun Nov 3 2019 by r003
4 !
5 version 15.0
6 service timestamps debug datetime msec
7 service timestamps log datetime msec
8 no service password-encryption
9 !
10 hostname BT-R003
11 !
12 boot-start-marker
13 boot-end-marker
14 !
15 !
16 no aaa new-model
17 dot11 syslog
18 ip source-route
19 !
20 !
21 !
22 !
23 ip cef
24 no ip domain lookup
25 ip domain name bt.lbboro
26 ipv6 unicast-routing
27 ipv6 cef
28 multilink bundle-name authenticated
29 !
30 !
31 !
32 !
33 !
34 !
35 !
36 !
37 !
38 voice-card 0
39 !
40 !
41 !
42 !
43 !
44 license udi pid CISCO2801 sn FCZ124112JK
```

APPENDIX A. ROUTERS CONFIGURATION

```
45 username r003 privilege 15 secret 5 $1$Jn3f$1SSIZA5X0c0JxuXDkz8rE/
46 !
47 !
48 ip ssh version 2
49 ip ssh dh min size 4096
50 ip ssh pubkey-chain
51 username r003
52   key-hash ssh-rsa 601E98BF47BA6CC0089AEC1177F6DEE5 root@BT001
53 !
54 !
55 !
56 !
57 !
58 interface Loopback0
59   ip address 23.0.255.3 255.255.255.255
60   ipv6 address 2001:2300:FFFF:3::/128
61 !
62 interface FastEthernet0/0
63   ip address 23.0.0.58 255.255.255.252
64   ip router isis
65   duplex auto
66   speed auto
67   ipv6 address 2001:2300:0:5::2/64
68   ipv6 router isis
69 !
70 interface FastEthernet0/1
71   ip address 23.0.0.54 255.255.255.252
72   ip router isis
73   duplex auto
74   speed auto
75   ipv6 address 2001:2300:0:4::2/64
76   ipv6 router isis
77 !
78 interface FastEthernet0/1/0
79   switchport access vlan 2
80 !
81 interface FastEthernet0/1/1
82   switchport access vlan 5
83 !
84 interface FastEthernet0/1/2
85   switchport access vlan 4
86 !
87 interface FastEthernet0/1/3
88 !
89 interface Vlan1
90   no ip address
91 !
```

APPENDIX A. ROUTERS CONFIGURATION

```
92 interface Vlan2
93   ip address 23.0.0.33 255.255.255.240
94   ip router isis
95   ipv6 address 2001:2300:0:2::1/64
96   ipv6 router isis
97 !
98 interface Vlan4
99   ip address 56.0.0.62 255.255.255.252
100  ipv6 address 2001:5600:0:6::2/64
101 !
102 interface Vlan5
103  ip address 100.100.2.2 255.255.255.252
104 !
105 router isis
106  net 49.0001.0230.0025.5003.00
107  is-type level-1
108  passive-interface Vlan4
109  passive-interface Vlan5
110  passive-interface Loopback0
111 !
112 router bgp 2030
113  no synchronization
114  bgp log-neighbor-changes
115  network 23.0.0.32 mask 255.255.255.240
116  aggregate-address 23.0.0.0 255.0.0.0 summary-only
117  neighbor 23.0.255.1 remote-as 2030
118  neighbor 23.0.255.1 update-source Loopback0
119  neighbor 23.0.255.2 remote-as 2030
120  neighbor 23.0.255.2 update-source Loopback0
121  neighbor 2001:2300:FFFF:1:: remote-as 2030
122  neighbor 2001:2300:FFFF:1:: update-source Loopback0
123  neighbor 2001:2300:FFFF:2:: remote-as 2030
124  neighbor 2001:2300:FFFF:2:: update-source Loopback0
125  neighbor 2001:5600:0:6::1 remote-as 5060
126  neighbor 56.0.0.61 remote-as 5060
127  neighbor 56.0.0.61 filter-list 1 out
128  neighbor 100.100.2.1 remote-as 42
129  neighbor 100.100.2.1 filter-list 1 out
130  no auto-summary
131 !
132 address-family ipv6
133  network 2001:2300:0:2::/64
134  aggregate-address 2001:2300::/32 summary-only
135  neighbor 2001:2300:FFFF:1:: activate
136  neighbor 2001:2300:FFFF:2:: activate
137 exit-address-family
138 !
```

APPENDIX A. ROUTERS CONFIGURATION

```
139 ip forward-protocol nd
140 !
141 ip as-path access-list 1 deny _42_
142 ip as-path access-list 1 deny _5060_
143 ip as-path access-list 1 permit .*
144 !
145 no ip http server
146 no ip http secure-server
147 !
148 !
149 !
150 !
151 control-plane
152 !
153 !
154 !
155 mgcp fax t38 ecm
156 mgcp behavior g729-variants static-pt
157 !
158 !
159 !
160 !
161 line con 0
162 line aux 0
163 line vty 0 4
164 login local
165 transport input telnet ssh
166 !
167 scheduler allocate 20000 1000
168 end
```

Appendix B

Laptops Configuration

B.1 Laptop 1 Configuration

B.2 Laptop 2 Configuration

B.3 Laptop 3 Configuration