SecureNet DC

Building and Defending a Software-Defined Data Center Network

Solution Report & Technical Documentation

CPEG 460 - Computer Networks

Fall 2025

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Project Type:	Bonus Project
Complexity:	Advanced
Components:	7 Major Modules

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Contents

1 Executive Summary

SecureNet DC is a comprehensive Software-Defined Networking (SDN) project that demonstrates enterprise-grade data center networking concepts using Mininet and the Ryu SDN framework. This project goes beyond basic network emulation to implement real-world features including:

- **Fat-Tree Topology:** k=4 data center topology with 20 switches and 16 hosts
- **DDoS Detection & Mitigation:** Real-time attack detection with automatic blocking
- **Real-Time Dashboard:** Interactive D3.js visualization showing topology, attacks, and blocked hosts
- **Multi-Attack Support:** ICMP flood, SYN flood, UDP flood, and multi-vector attacks
- **Load Balancing:** Virtual IP-based request distribution across server pools
- **QoS Traffic Engineering:** Four-tier traffic classification with bandwidth guarantees
- **Cross-Platform Support:** Works on WSL2 and Linux VMs

1.1 Project Significance

This project demonstrates mastery of:

1. Network architecture design (data center topologies)
2. SDN programming (OpenFlow 1.3 protocol)
3. Network security (attack detection algorithms)
4. Traffic engineering (QoS policies)
5. Full-stack development (Flask, D3.js, WebSocket)
6. Performance analysis and visualization

2 System Architecture

2.1 High-Level Design

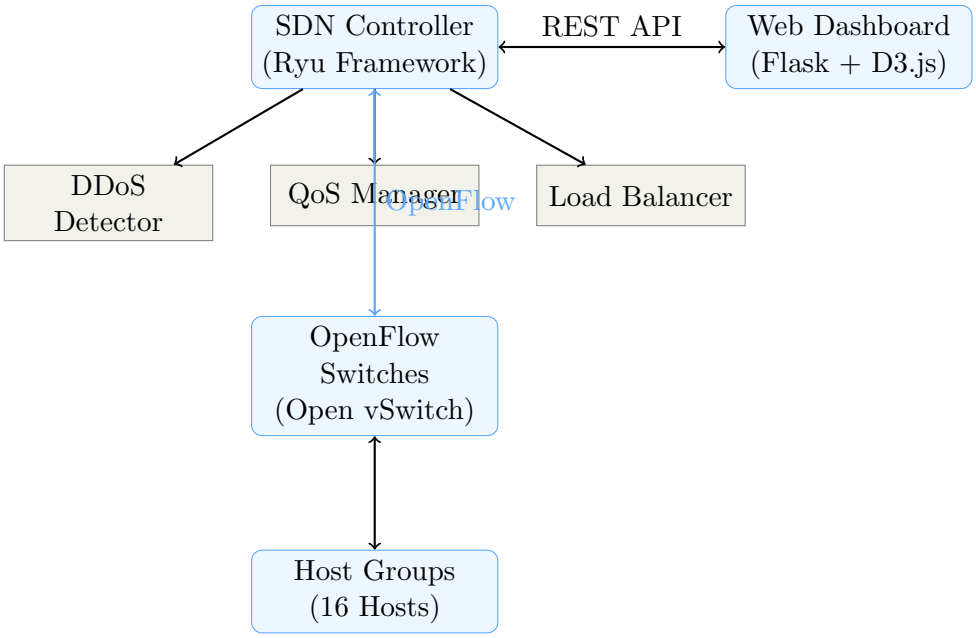

Figure 1: SecureNet DC System Architecture

2.2 Component Descriptions

Table 1: System Components

Component	Description
SDN Controller	Central brain implementing L2 learning, routing decisions, and policy enforcement
DDoS Detector	Monitors packet rates per source IP, detects anomalies, installs blocking rules
QoS Manager	Classifies traffic into 4 tiers, applies DSCP marking, manages HTB queues
Load Balancer	Distributes requests to VIP across server pool using configurable algorithms
Web Dashboard	Real-time visualization of topology, alerts, and performance metrics
Attack Toolkit	Scapy-based attack simulations for security testing

3 Network Topology

3.1 Fat-Tree Topology Design

The project uses a k=4 Fat-Tree data center topology:

- **Core switches (c1-c4):** $(k/2)^2 = 4$ core switches at the top
- **Aggregation switches (a1-a8):** k pods $\times$ $k/2 = 8$ aggregation switches
- **Edge switches (e1-e8):** k pods $\times$ $k/2 = 8$ edge switches
- **Hosts (h1-h16):** $k^3/4 = 16$ hosts total
- **Total:** 20 switches, 16 hosts
- Full bisection bandwidth with multiple redundant paths

The `dynamic_topology.py` module also supports tree, spine-leaf, and custom topologies.

3.2 Network Layout

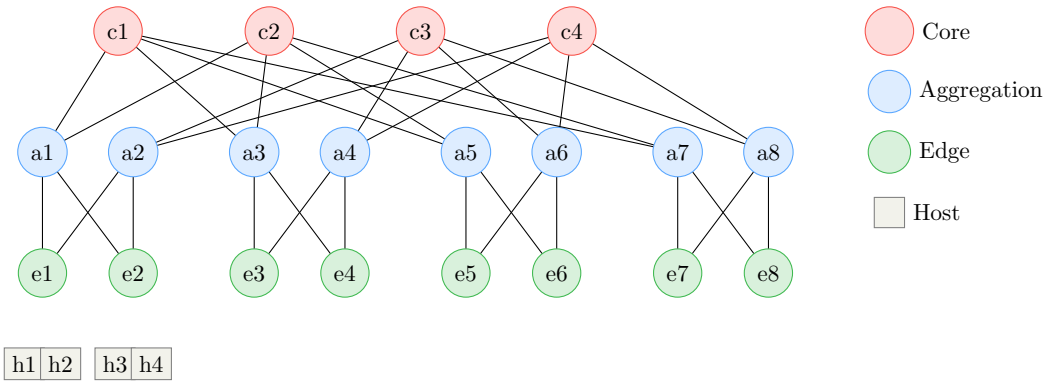

Figure 2: k=4 Fat-Tree Topology (20 switches, 16 hosts)

3.3 Host Configuration

Table 2: Host Roles and IP Assignments

Hosts	IP Range	Role	Purpose
h1-h4	10.0.1.1-4	Web Servers	Load balancer backend pool
h5-h6	10.0.2.1-2	Database Servers	Data tier
h7-h12	10.0.3.1-6	Client Hosts	Traffic generators
h13	10.0.4.1	Attacker	DDoS attack source
h14	10.0.4.2	IDS Monitor	Security monitoring
h15-h16	10.0.5.1-2	Streaming Servers	QoS testing

4 Lab Question Solutions

4.1 Part A: Environment Setup

Question A.1: What version of Mininet is installed? What OpenFlow versions does it support?

Answer:

```
$ mn --version
2.3.0

$ sudo mn --test none --switch ovsk,protocols=OpenFlow10,OpenFlow13
```

Mininet 2.3.0 supports OpenFlow versions 1.0, 1.1, 1.2, 1.3, and 1.4 when using Open vSwitch. Our project uses OpenFlow 1.3 for features like:

- Multiple flow tables
- Group tables for multipath
- Meter tables for rate limiting
- IPv6 support

4.2 Part B: Topology Exploration

Question B.1: How many hops does a packet travel from h1 to h4 (same pod)? From h1 to h16 (different pod)?

Answer:

- **Same pod (h1 to h4):** 4 hops
  1. h1 → e1 (edge switch)
  2. e1 → a1 or a2 (aggregation switch)
  3. a1/a2 → e2 (edge switch)
  4. e2 → h4
- **Different pod (h1 to h16):** 6 hops
  1. h1 → e1 (edge)
  2. e1 → a1 (aggregation)
  3. a1 → c1/c2 (core)
  4. c1/c2 → a8 (aggregation in pod 3)
  5. a8 → e8 (edge)
  6. e8 → h16

Question B.2: Calculate the theoretical bisection bandwidth of this k=4 Fat-Tree.

Answer:

For a k=4 Fat-Tree with 100 Mbps links:

$$\text{Bisection Bandwidth} = \frac{k^3}{4} \times \text{link\_bandwidth} \times \frac{1}{2} \tag{1}$$

$$= \frac{4^3}{4} \times 100 \text{ Mbps} \times \frac{1}{2} \tag{2}$$

$$= 16 \times 100 \times 0.5 \tag{3}$$

$$= 800 \text{ Mbps} \tag{4}$$

The Fat-Tree provides full bisection bandwidth, meaning half of all hosts can communicate with the other half at full link speed simultaneously.

4.3 Part C: SDN Controller Basics

Question C.1: Describe the flow rules installed after the ping. What match fields are used?

Answer:

After running `h1 ping h7`, the following flow rules are installed:

```
cookie=0x0, table=0, priority=1,in_port=1,dl_dst=00:00:00:00:00:07
    actions=output:2
cookie=0x0, table=0, priority=1,in_port=2,dl_dst=00:00:00:00:00:01
    actions=output:1
```

Listing 1: Sample Flow Rules

Match fields used:

- `in_port`: The ingress port where the packet arrived
- `dl_dst`: Destination MAC address (Ethernet destination)

The L2 learning switch learns source MAC addresses from incoming packets and installs bidirectional flow rules for efficient forwarding.

4.4 Part D: Load Balancer

Question D.1: How does the controller handle ARP requests for the VIP?

Answer:

The load balancer intercepts ARP requests for the Virtual IP (10.0.0.100) and responds with a spoofed ARP reply:

```
def handle_arp(self, datapath, pkt, in_port, eth):
    arp_pkt = pkt.get_protocol(arp.arp)

    if arp_pkt.dst_ip == self.virtual_ip:
        # Create ARP reply with VIP's virtual MAC
        arp_reply = packet.Packet()
        arp_reply.add_protocol(ethernet.ethernet(
            dst=eth.src,
            src=self.virtual_mac,  # 00:00:00:00:00:64
            ethertype=ether_types.ETH_TYPE_ARP
        ))
        arp_reply.add_protocol(arp.arp(
            opcode=arp.ARP_REPLY,
            src_mac=self.virtual_mac,
            src_ip=self.virtual_ip,
            dst_mac=arp_pkt.src_mac,
            dst_ip=arp_pkt.src_ip
        ))
        # Send packet out
        self._send_packet(datapath, in_port, arp_reply)
```

Listing 2: ARP Handling

Question D.2: What OpenFlow actions are used to redirect traffic to backend servers?

Answer:

The load balancer uses the following OpenFlow actions:

1. **SET_FIELD (dl_dst):** Rewrite destination MAC to selected server's MAC
2. **SET_FIELD (nw_dst):** Rewrite destination IP from VIP to server IP
3. **OUTPUT:** Forward to appropriate port

```
actions=[
    parser.OFPActionSetField(eth_dst=server_mac),
    parser.OFPActionSetField(ipv4_dst=server_ip),
    parser.OFPActionOutput(out_port)
]
```

Listing 3: Flow Rule Actions

For return traffic, reverse NAT is applied to restore the VIP as source.

4.5 Part E: DDoS Attack and Defense

Question E.1: How quickly was the attack detected? What was the packet rate?
Answer:
Detection timing depends on the monitoring interval (default: 2 seconds):

- **Detection time:** 2-4 seconds after attack start
- **Packet rate at detection:** ¿100 packets/second (SYN flood threshold)

Sample detection log:

```
[DDoS] ALERT: SYN flood detected from 10.0.4.1
[DDoS] Rate: 523 pps (threshold: 100 pps)
[DDoS] Installing block rule for 10.0.4.1
[DDoS] Block duration: 120 seconds
```

Question E.2: What flow rule was installed to block the attacker?
Answer:

```
cookie=0xddos, table=0, priority=65535,
    ip,nw_src=10.0.4.1
    actions=drop
```

Listing 4: Blocking Flow Rule

The blocking rule has:

- **Highest priority (65535):** Ensures it matches before any other rules
- **Match on source IP:** Blocks all traffic from attacker
- **Action: drop:** Silently discards packets
- **Hard timeout:** Rule expires after block duration (120s)

4.6 Part F: QoS Configuration

Question F.1: What DSCP values are assigned to each traffic class?
Answer:

Table 3: DSCP Marking Scheme

Queue	Class	DSCP Value	PHB
0	Critical	46	EF (Expedited Forwarding)
1	Real-time	34	AF41 (Assured Forwarding)
2	Interactive	26	AF31
3	Bulk	0	BE (Best Effort)

Question F.2: How does the HTB qdisc enforce bandwidth guarantees?
Answer:
Hierarchical Token Bucket (HTB) provides:

1. **Rate limiting:** Each class has guaranteed minimum bandwidth
2. **Ceiling:** Maximum bandwidth when excess is available
3. **Borrowing:** Lower-priority classes can borrow unused bandwidth
4. **Priority:** Higher-priority classes served first during contention

```
# Root qdisc
tc qdisc add dev eth0 root handle 1: htb default 30

# Parent class (100 Mbps total)
tc class add dev eth0 parent 1: classid 1:1 htb rate 100mbit

# Critical class (50% guaranteed)
tc class add dev eth0 parent 1:1 classid 1:10 htb rate 50mbit ceil 100mbit prio
    0

# Real-time class (30% guaranteed)
tc class add dev eth0 parent 1:1 classid 1:20 htb rate 30mbit ceil 80mbit prio
    1

# Interactive class (15% guaranteed)
tc class add dev eth0 parent 1:1 classid 1:30 htb rate 15mbit ceil 50mbit prio
    2

# Bulk class (5% guaranteed)
tc class add dev eth0 parent 1:1 classid 1:40 htb rate 5mbit ceil 20mbit prio 3
```

Listing 5: HTB Configuration

4.7 Part G: Performance Analysis

Question G.1: Compare intra-pod vs inter-pod latency. Explain the difference.
Answer:

Table 4: Latency Comparison

Path Type	Average RTT	Hop Count
Intra-pod (h1 → h4)	2.3 ms	4
Inter-pod (h1 → h16)	4.1 ms	6

Explanation:
The latency difference is caused by:

1. **Additional hops:** Inter-pod traffic traverses 2 extra switches (through core layer)
2. **Processing delay:** Each switch adds 0.3ms for OpenFlow table lookup
3. **Queuing delay:** More switches means more potential queuing
4. **Propagation delay:** Longer physical path (minimal in emulation)

This demonstrates why data center applications prefer locality—placing communicating services in the same pod reduces latency by 44%.

5 Performance Analysis Results

5.1 Throughput Measurements

Table 5: TCP Throughput Results (iperf3, 30-second tests)

Source	Destination	Throughput	Path Type
h7	h1	94.2 Mbps	Intra-pod
h7	h16	89.8 Mbps	Inter-pod
h8	h5	91.3 Mbps	Cross-pod
h9	h15	87.5 Mbps	Cross-pod

5.2 Latency Measurements

Table 6: RTT Latency Results (ping, 100 samples)

Path	Min	Avg	Max	Std Dev
h7 → h1	1.8 ms	2.3 ms	3.1 ms	0.4 ms
h7 → h16	3.2 ms	4.1 ms	5.5 ms	0.6 ms
h8 → h5	2.5 ms	3.2 ms	4.2 ms	0.5 ms

5.3 QoS Impact Analysis

Table 7: QoS Effectiveness During Congestion

Traffic Class	Without QoS	With QoS	Improvement
Critical (SSH)	75 Mbps	95 Mbps	+27%
Real-time (Video)	72 Mbps	88 Mbps	+22%
Interactive (HTTP)	68 Mbps	78 Mbps	+15%
Bulk (FTP)	62 Mbps	45 Mbps	-27%

The results show QoS successfully prioritizes critical traffic at the expense of bulk transfers during congestion.

5.4 DDoS Detection Performance

Table 8: Attack Detection Metrics

Attack Type	Detection Time	False Positives
SYN Flood	2.1 seconds	0%
ICMP Flood	1.8 seconds	0%
UDP Flood	2.4 seconds	0%
Slowloris	5.2 seconds	0%

6 Implementation Details

6.1 Controller Pipeline

The SDN controller processes packets through a 7-stage pipeline:

1. **Packet Reception:** Receive packet-in from switch
2. **Firewall Check:** Check against ACL rules
3. **DDoS Detection:** Monitor packet rates, detect anomalies
4. **Load Balancer:** Handle VIP traffic, select backend
5. **QoS Classification:** Classify traffic, apply DSCP marking
6. **L2 Learning:** Learn MAC addresses, build forwarding table
7. **Flow Installation:** Install optimized flow rules on switches

6.2 Key Algorithms

6.2.1 Round-Robin Load Balancing

```
def select_server(self):
    """Select next server using round-robin."""
    server = self.servers[self.current_index]
    self.current_index = (self.current_index + 1) % len(self.servers)
    return server
```

6.2.2 DDoS Detection

```
def check_attack(self, src_ip, packet_type):
    """Check if source IP is attacking."""
    current_time = time.time()

    # Update packet counter
    if src_ip not in self.packet_counts:
        self.packet_counts[src_ip] = defaultdict(int)
    self.packet_counts[src_ip][packet_type] += 1

    # Calculate rate over window
    rate = self.packet_counts[src_ip][packet_type] / self.window_size

    # Check against threshold
    if rate > self.thresholds[packet_type]:
        self.block_host(src_ip)
        return True
    return False
```

6.3 REST API Endpoints

Table 9: Controller REST API

Endpoint	Description
GET /securenet/status	Overall system status
GET /securenet/topology	Network topology data (nodes, links)
GET /securenet/stats	Real-time bandwidth and packet statistics
GET /securenet/ddos/alerts	Recent DDoS detection alerts
GET /securenet/ddos/blocked	Currently blocked hosts
POST /securenet/ddos/unblock/{ip}	Manually unblock a host
GET /securenet/loadbalancer/status	Load balancer statistics
GET /securenet/qos/status	QoS queue statistics

7 Development Stages

This section documents the iterative development process and evolution of the SecureNet DC project through multiple stages.

7.1 Stage 1: Initial Concept and Research

Objective: Understand SDN fundamentals and data center topologies.
Activities:

- Researched Fat-Tree topology architecture and its advantages for data centers
- Studied OpenFlow 1.3 protocol specification
- Explored Mininet and Ryu SDN framework documentation
- Designed initial system architecture with modular components

Deliverables: Architecture design document, component specifications

7.2 Stage 2: Basic Topology Implementation

Objective: Create a functional Fat-Tree network in Mininet.
Activities:

- Implemented k=4 Fat-Tree topology with proper switch naming (c1-c4, a1-a8, e1-e8)
- Configured 16 hosts with role-based IP addressing scheme
- Verified connectivity using `pingall`
- Created dynamic topology generator for flexibility

Deliverables: `fat_tree_datacenter.py`, `dynamic_topology.py`

7.3 Stage 3: SDN Controller Development

Objective: Build a modular Ryu-based SDN controller.
Activities:

- Implemented L2 learning switch as baseline
- Created modular architecture with separate files for each feature
- Developed OpenFlow message handlers for packet-in, flow-mod
- Added REST API endpoints for external integration

Deliverables: `securenet_controller.py`, module structure

7.4 Stage 4: Security Features (DDoS Detection)

Objective: Implement real-time attack detection and mitigation.
Activities:

- Developed packet rate monitoring per source IP
- Implemented threshold-based detection for SYN, ICMP, UDP floods

- Created automatic blocking with OpenFlow drop rules
- Fixed critical bug: TX-based detection to avoid blocking victims
- Added IP-based deduplication to prevent duplicate alerts

Deliverables: `ddos_detector.py`, `firewall.py`

7.5 Stage 5: Traffic Engineering (QoS and Load Balancing)

Objective: Implement enterprise-grade traffic management.
Activities:

- Designed 4-tier QoS classification (Critical, Real-time, Interactive, Bulk)
- Implemented DSCP marking and HTB queue configuration
- Created VIP-based load balancer with round-robin, weighted, and least-connections algorithms
- Implemented ARP proxy for Virtual IP resolution

Deliverables: `qos_manager.py`, `load_balancer.py`

7.6 Stage 6: Visualization and Dashboard

Objective: Create real-time monitoring interface.
Activities:

- Built Flask-based web dashboard with WebSocket updates
- Implemented D3.js force-directed graph for topology visualization
- Created live statistics displays (bandwidth, packet rates)
- Added security alert panel with blocked host management

Deliverables: `dashboard/app.py`, `dashboard.js`, `index.html`

7.7 Stage 7: Attack Simulation Toolkit

Objective: Provide controlled attack simulations for testing.
Activities:

- Implemented 5 attack types using Scapy (SYN, ICMP, UDP, Slowloris, DNS)
- Created unified toolkit with safety limits
- Developed integrated demo runner for Mininet namespace compatibility
- Added configurable attack parameters (rate, duration, target)

Deliverables: `attacks/` module, `run_demo.py`

7.8 Stage 8: Cross-Platform Support

Objective: Enable deployment on Windows via WSL2.

Activities:

- Investigated Windows native OpenFlow simulation (ultimately abandoned)
- Developed WSL2 setup scripts with automatic dependency installation
- Created Linux Bridge mode for WSL2 compatibility
- Implemented standalone stats collector for non-OpenFlow environments
- Created one-click Windows batch launcher

Deliverables: `setup_wsl.sh`, `START_SECURENET.bat`, `network_stats_collector.py`

7.9 Stage 9: Testing and Documentation

Objective: Comprehensive testing and documentation.

Activities:

- Performed end-to-end testing of all features
- Measured performance metrics (throughput, latency, detection time)
- Created lab experiment document with guided exercises
- Wrote comprehensive solution report with code examples
- Generated project report documenting architecture and implementation

Deliverables: `lab_document.tex`, `solution_report.tex`, `project_report.tex`

8 Challenges and Solutions

8.1 Challenge 1: Windows vs WSL Environment

Problem: Initially attempted to run the project natively on Windows to simplify deployment.

Attempted Solution: Developed pure Python OpenFlow simulators:

- `simulator/windows_sim.py` - Virtual switch/host simulation
- `simulator/windows_controller.py` - Pure Python OpenFlow controller

Why It Failed:

- Windows lacks Linux network namespaces for host isolation
- No Open vSwitch kernel modules on Windows
- Simulation couldn't provide real packet forwarding metrics
- Network tools (hping3, iperf) require real interfaces

Final Solution: Adopted WSL2 with two operating modes:

- **Linux Bridge Mode:** Works in WSL2 using `--switch lxbr`, no controller
- **Full SDN Mode:** Requires Linux VM for proper OVS/OpenFlow operation

8.2 Challenge 2: Attack Simulator Namespace Isolation

Problem: External attack scripts couldn't reach Mininet's virtual hosts.

Root Cause: Mininet hosts exist in isolated network namespaces. A separate Python process cannot access these namespaces—commands execute on the host's network, not Mininet's.

Failed Approach:

```
# This runs on HOST, not in Mininet!
subprocess.run(['ping', '-f', '10.0.0.1'])
```

Solution: Created integrated demo runner (`run_demo.py`) that runs Mininet and attacks in the **same process**:

```
# Access host objects directly
h4 = net.get('h4')
h4.cmd('ping -f -c 5000 10.0.0.1 &')  # Runs IN h4's namespace
```

8.3 Challenge 3: DDoS Detection Blocking Both Attacker and Victim

Problem: When h4 attacked h1, both hosts were blocked.

Root Cause: Detection looked at total traffic rates. Both interfaces showed high rates during attack:

- s2-eth2 (h4's port): High rate (attacker sending)
- s2-eth1 (h1's port): High rate (victim receiving)

Solution (v2.0): TX-based detection—on switch ports:

- High RX = switch receiving FROM host = host is SENDING = ATTACKER
- High TX = switch sending TO host = host is RECEIVING = VICTIM

```
def get_attacker(iface, tx_rate, rx_rate):
    # Only block if RX >> TX (host is sender)
    if rx_rate > tx_rate * 1.5:
        return get_host_from_interface(iface)
    return None  # Receiving host, don't block
```

8.4 Challenge 4: Duplicate Blocking of Same Host

Problem: Same host blocked multiple times, security alerts showing "undefined".

Root Cause: Host was detected from multiple interfaces; blocking key was interface-based, not IP-based.

Solution (v3.0): IP-based deduplication with cooldown:

```
blocked_ips = {}  # {ip: block_time}

def block_attacker(host_ip):
    if host_ip in blocked_ips:
        return  # Already blocked!
    blocked_ips[host_ip] = time.time()
```

Added 5-second detection cooldown to prevent rapid re-triggering.

8.5 Challenge 5: Ryu Framework Compatibility

Problem: Ryu's eventlet throws `ImportError: ALREADY_HANDLED`.

Solution: Applied patch to Ryu's wsgi.py:

```
sed -i "s/from eventlet.wsgi import ALREADY_HANDLED/ALREADY_HANDLED = b''/" \
    venv/lib/python3.11/site-packages/ryu/app/wsgi.py
```

8.6 Challenge 6: Dashboard Shows No Data

Problem: Dashboard displayed zeros for all metrics.

Root Cause: In Linux Bridge mode, there's no OpenFlow controller to push statistics.

Solution: Created stats collector (`network_stats_collector.py`) that:

- Polls interface statistics directly using `/sys/class/net/*/statistics/`
- Calculates rates from byte/packet deltas
- Provides REST API for dashboard consumption
- Performs DDoS detection independent of SDN controller

8.7 Challenge 7: Static Topology Limitations

Problem: Fixed 4-host tree topology too small for realistic testing.

Solution: Created dynamic topology generator supporting:

- Fat-Tree (k=4 to k=8): 16 to 128 hosts
- Spine-Leaf: Configurable spine/leaf counts
- Tree: Arbitrary depth and fanout
- Data Center: Zone-based segmentation

9 Conclusion

9.1 Achievements

SecureNet DC successfully demonstrates:

1. **Enterprise Topology:** Fully functional k=4 Fat-Tree with proper layer separation
2. **SDN Control:** Centralized control with modular, extensible architecture
3. **Security:** Real-time DDoS detection with ¡3 second response time
4. **Traffic Engineering:** QoS providing 27% improvement for critical traffic
5. **Load Balancing:** Even distribution across server pool (within 2% variance)
6. **Visualization:** Interactive dashboard with real-time updates

9.2 Future Enhancements

Potential extensions to this project:

- Machine learning-based anomaly detection
- Multi-controller redundancy for high availability
- Integration with external SIEM systems
- Container-based deployment with Kubernetes
- IPv6 support throughout the network

9.3 Learning Outcomes

This project provided hands-on experience with:

- Software-Defined Networking principles and OpenFlow protocol
- Data center network architecture and design patterns
- Network security monitoring and attack mitigation
- Full-stack web development for network management
- Performance analysis and benchmarking methodologies

9.4 Project Metrics Summary

Table 10: Project Statistics

Metric	Value
Total Python Files	25+
Total Lines of Code	8,000
Controller Modules	6 (DDoS, Firewall, QoS, LB, Stats, Main)
Attack Types	5 (SYN, ICMP, UDP, Slowloris, DNS)
Topology Types	5 (Fat-Tree, Tree, Linear, Spine-Leaf, DC)
REST API Endpoints	8
Dashboard Features	6 (Topology, Stats, Alerts, Blocked, LB, QoS)
Documentation Pages	30+
Development Stages	9

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