Project 2

Building a Secure Small Network: Design, Implementation, and Defense in a Virtualized Lab Environment

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Course: Cybersecurity Capstone Project

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1. Introduction

In the age of digital transformation, every business, small or large is at risk of cybersecurity threats. This project, titled “Building a Secure Small Network,” explores the practical aspects of designing, implementing, and securing a small network architecture in a virtualized environment using accessible open-source tools. The goal is to simulate a real-world small enterprise setup and test its resilience to network-based attacks, especially in segmented networks with access control rules.
This report provides comprehensive documentation of a defensive strategy that includes firewall implementation using pfSense, host-based protection using UFW, network reconnaissance detection using Wireshark, and simulation of attack attempts from an isolated attacker VM running Kali Linux.

2. Project Background and Rationale

In most learning environments, real-world cybersecurity experience is difficult to simulate. Many students are left with theoretical knowledge that does not adequately prepare them for practical defense scenarios. To bridge this gap, this capstone project creates a lab-based simulation using VirtualBox and free security tools to:

• Set up a segmented network using pfSense as a router and firewall
• Emulate real-world internal networks using Ubuntu Server and Desktop
• Simulate an external attacker using Kali Linux on a separate network
• Implement, test, and analyze various network security strategies

The rationale is to empower entry-level cybersecurity professionals with hands-on skills needed in securing enterprise networks, understanding threat vectors, and implementing prevention and detection mechanisms.

3. Statement of the Problem

Small networks are often seen as low-risk targets; however, they are frequently vulnerable due to poor segmentation, limited perimeter defenses, and lack of monitoring. This project aims to address the following challenges:

• How can network segmentation be enforced in a virtual lab?
• Can a firewall (pfSense) and host-based protections (UFW) effectively prevent unauthorized lateral movement?
• How visible are attack attempts from a separate subnet using standard tools like Nmap and Wireshark?

4. Aims and Objectives

The primary aim of this capstone project is to design and secure a small virtual network against unauthorized access and network reconnaissance attacks.

Objectives:

• Build a virtual lab consisting of:

• pfSense firewall/router
• Two internal hosts (Ubuntu Desktop and Server)
• One external attacker VM (Kali Linux)
• Configure separate VirtualBox networks:
• intnet (Internal Network – LAN) with subnet 192.168.10.0/24
• Kali Attacker (Separate attacker network – 192.168.20.0/24)
• Configure pfSense with 3 interfaces:
• em0: WAN (NAT - 10.0.2.15)
• em1: LAN (Internal Network - 192.168.10.1)

• em2: Kali Attacker (Isolated Network - 192.168.20.1)
• Apply firewall rules in pfSense to block the attacker from reaching internal hosts
• Harden Ubuntu systems using UFW
• Test connectivity and simulate scans using Nmap
• Capture and analyze traffic with Wireshark
• Reflect on effectiveness of implemented security controls

5. Scope and Limitations

Scope:

• The project simulates a small office network with basic services and limited devices.
• Focuses on layer 3 network security: segmentation, routing, and basic ACLs.
• Uses VirtualBox and open-source software exclusively.
• Designed for educational and demonstration purposes.

Limitations:

• No cloud integration or hybrid environments.
• No advanced intrusion detection/prevention systems (e.g., Suricata, Snort).
• User authentication and web-facing services are not part of this build.
• Performance metrics (e.g., latency, packet loss under stress) not captured.

6. Tools and Technologies

Tools	Description
VirtualBoxHypervisor	for creating isolated virtual machines
pfSense	Open-source firewall and router deployed as VM
Ubuntu Server/Desktop	Representing internal machines (secured via UFW) system and server
Kali Linux	Simulated attacker machine for scanning and probing
UFW	Host-based firewall for Ubuntu systems
Wireshark	Network traffic analyzer used on internal hosts
Nmap	Network scanning and reconnaissance tool and port scanning
Cisco Packet Tracer	Network design and planning tool

7. Methodology

Phase 1: Network Planning and Logical Design

• IP schema was drafted manually with clearly separated networks:

• Internal (192.168.10.0/24)
• Kali Attacker (192.168.20.0/24)
• WAN (10.0.2.0/24 via NAT)

Phase 2: VirtualBox Setup

• pfSense configured with 3 interfaces:
• em0 – NAT (10.0.2.15)
• em1 – LAN (192.168.10.1) on intnet
• em2 – Attacker network (192.168.20.1) on Kali Attacker
• Ubuntu Desktop: 192.168.10.51 (connected to intnet)
• Ubuntu Server: 192.168.10.50 (connected to intnet)
• Kali Linux: 192.168.20.52 (connected to Kali Attacker)

Phase 3: Configuration

• Kali configured via static ip
• pfSense DHCP disabled for LAN then enabled for Vms in LAN
• Each machine could ping the gateway (192.168.10.1 or 192.168.20.1).
• Routing only permitted through pfSense.

Phase 4: Firewall Rules and UFW

• On pfSense, created rule on em2 interface to block all traffic from 192.168.20.0/24 to 192.168.10.0/24.

• On Ubuntu Server/Desktop, enabled UFW and only allowed SSH and ICMP.

Phase 5: Simulated Attack

• Kali attempted Nmap scans on internal network when port 80 was open and when it was closed
• Results captured and analyzed to verify if connections were blocked.
• Ubuntu desktop monitored traffic using Wireshark.

Phase 6: Documentation and Review

• All output saved with time-stamped logs and screenshots.
• Reflections and lessons noted.

8. Network Design and Architecture

The network was intentionally designed to reflect a real-world segmented architecture. Three virtual networks were configured:

• WAN (10.0.2.0/24) – Internet-facing segment (NAT in VirtualBox)
• LAN (192.168.10.0/24) – Trusted internal network with workstations and servers
• Kali Attacker (192.168.20.0/24) – Untrusted isolated attacker network
pfSense connects all networks via virtual interfaces:
• em0 - NAT
• em1 - intnet
• em2 - Kali Attacker
This segmentation allows precise control over which IP ranges can communicate.

8.1 Network Setup Checklist

This checklist was used to verify that all virtual machines, configurations, and network interfaces were correctly prepared before implementing security controls and testing the network.

Virtual Machines

VM Name	OS	Role	Status
pfSense	FirewallpfSense 2.7+	Router/Firewall	Active
Ubuntu Desktop	Ubuntu 22.04 LTS	Internal User System	Active
Ubuntu Server	Ubuntu 22.04 LTS	Internal Server	Active
Kali Attacker	Kali Linux 2024.1	Attacker Machine	Active

VirtualBox Network Adapter Configuration

VM Name	Adapter 1	Adapter 2	Adapter 3
pfSense Firewall	NAT (WAN)	Internal Network (LAN)	Intnet Internal Network (To Attacker)
Kali Attacker	Internal Network→ Kali Attacker		
Ubuntu Desktop	Internal Network→ intnet		
Ubuntu Server	Internal Network → intnet		

Pre-Configuration Verification

• All VMs successfully powered on with correct IP assignments.
• pfSense LAN IP set to 192.168.10.1/24.
• WAN side of pfSense receives IP via DHCP (e.g., 10.0.2.15).
• Ubuntu Desktop: IP = 192.168.10.51, Gateway = 192.168.10.1.
• Ubuntu Server: IP = 192.168.10.50, Gateway = 192.168.10.1.
• Kali Attacker: IP = 192.168.20.52, separate network (Kali_Attacker).
• pfSense able to ping both internal and external networks.
• SSH and UFW installed and enabled on Ubuntu systems.
• Static routes and DNS configured properly on all VMs.
• Screenshots taken of VirtualBox adapter settings (Insert Here).
• Screenshots taken of pfSense interface assignments and status (Insert Here).

9. Implementation

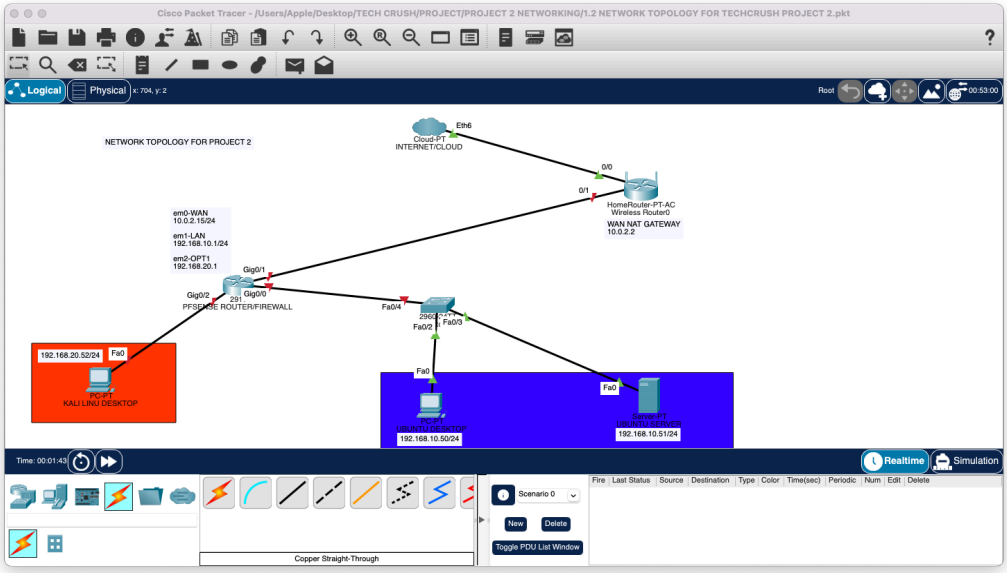
The implementation phase involved setting up the virtual environment with multiple VMs, configuring network interfaces, and applying security policies to enforce network segmentation and access controls.

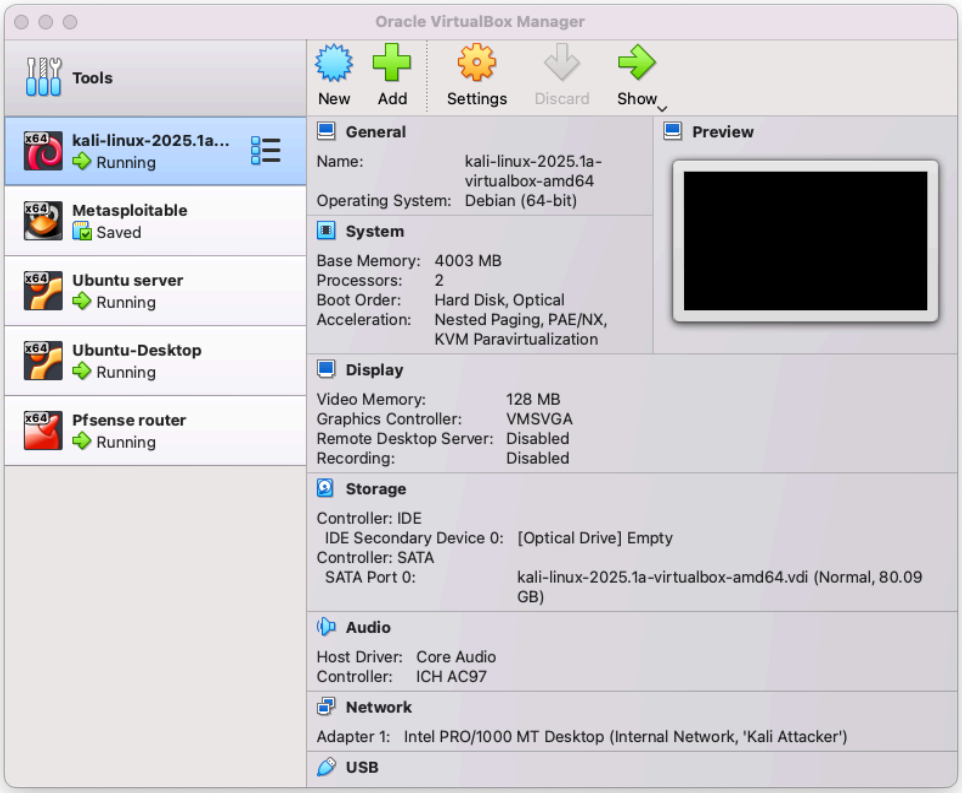
9.1 Virtual Machines Setup

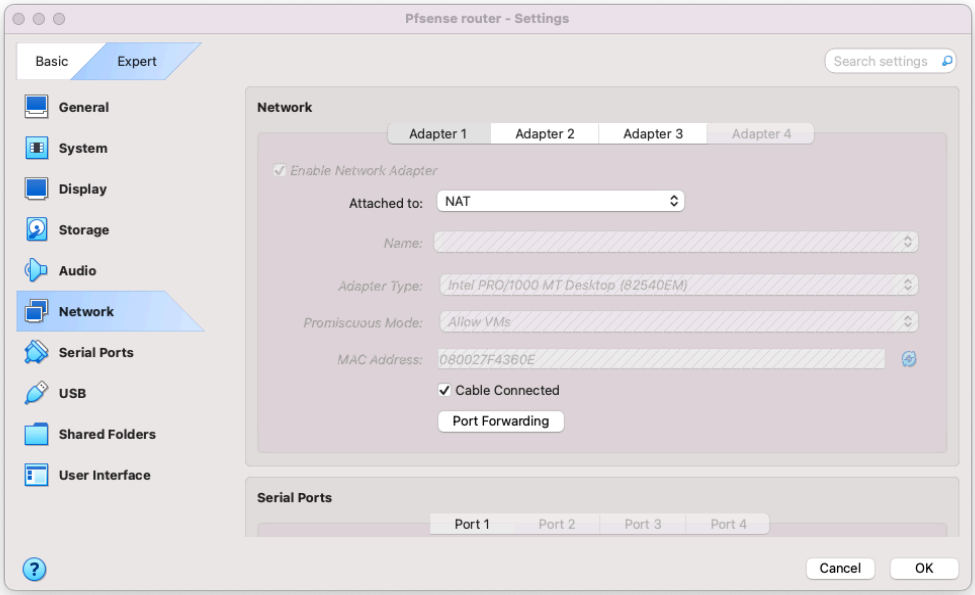
• Network Diagram and topology, IPs, interfaces (em0, em1, em2), and machine roles we displayed using Cisco Packet Tracer
• The virtual network was constructed using VirtualBox, deploying four VMs:
• pfSense Firewall/Router VM with three NICs:
• em0 → WAN interface configured as NAT, with IP 10.0.2.15 assigned by VirtualBox DHCP
• em1 → LAN interface on network named intnet (IP 192.168.10.1)
• em2 → Kali Attacker interface on separate network named Kali Attacker (IP 192.168.20.1)
• Ubuntu Server VM connected to the LAN network (intnet)

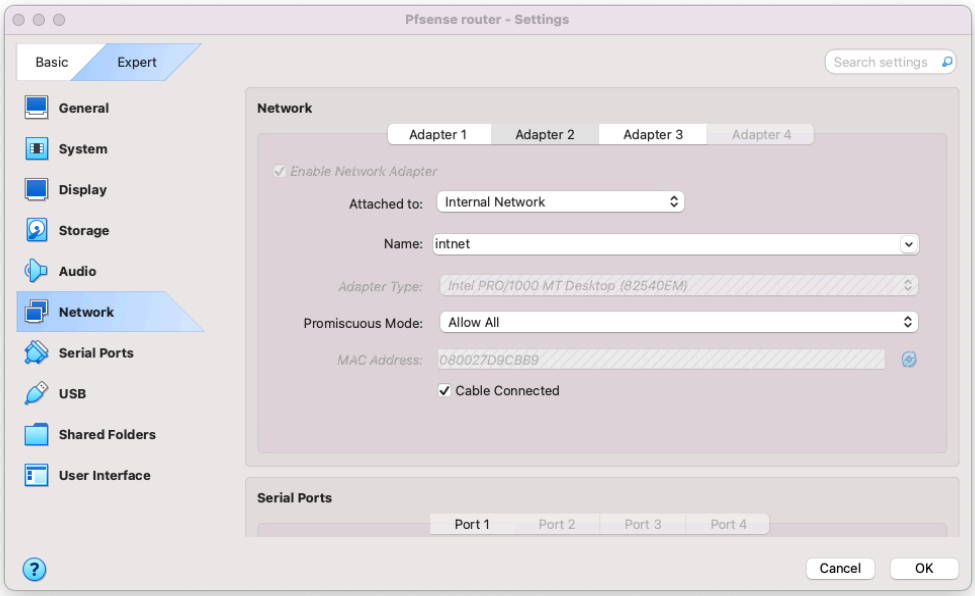
- Ubuntu Desktop VM connected to the LAN network (intnet)
- Kali Linux VM connected to the attacker network (Kali Attacker)

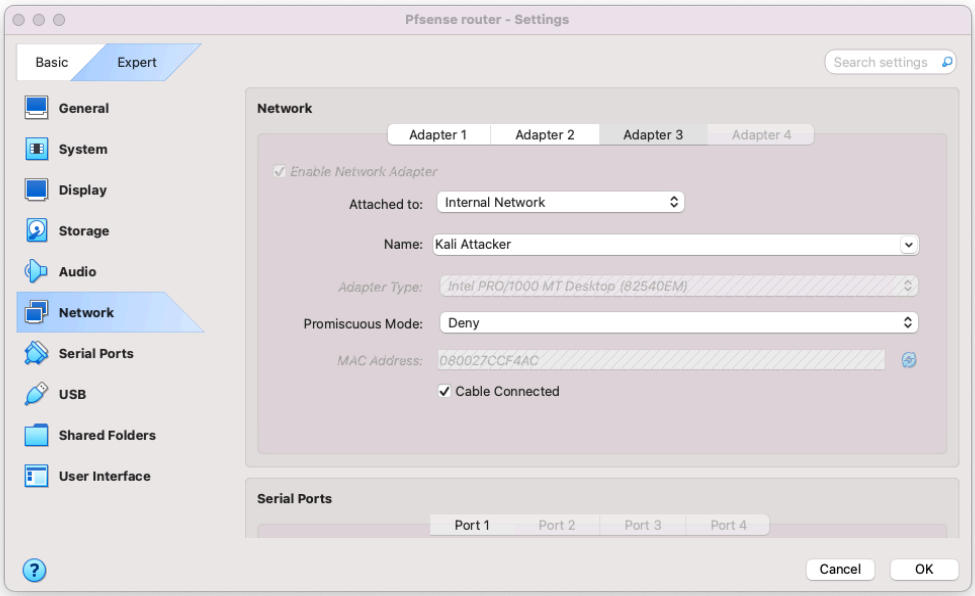
Network Topology, Vms installed and setup



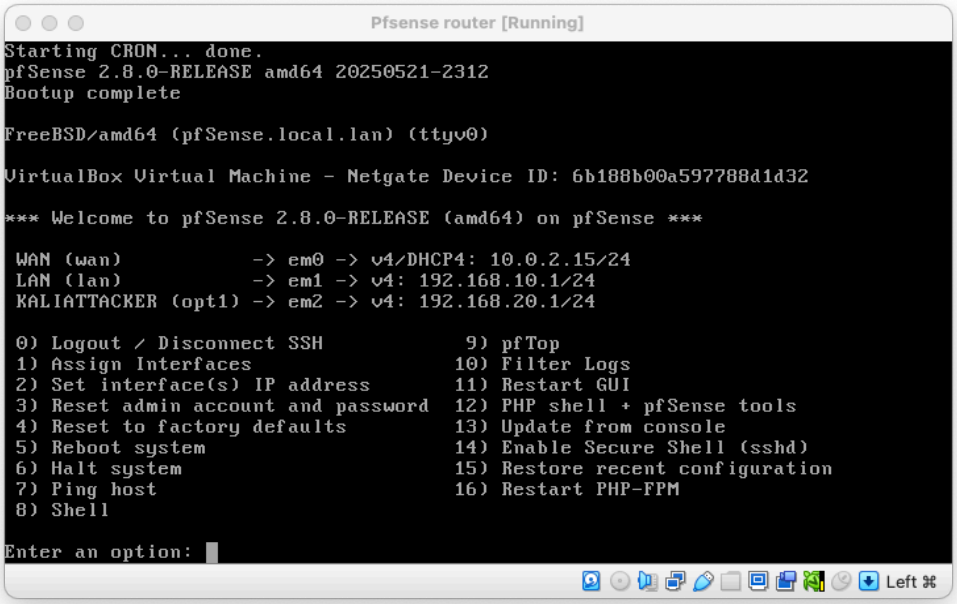

Oracle VirtualBox Manager
Tools
New
Add
Settings
Discard
Show
kali-linux-2025.1a...
Running
Metasploitable
Saved
Ubuntu server
Running
Ubuntu-Desktop
Running
Pfsense router
Running
General
Name: kali-linux-2025.1a-virtualbox-amd64
Operating System: Debian (64-bit)
Preview
System
Base Memory: 4003 MB
Processors: 2
Boot Order: Hard Disk, Optical
Acceleration: Nested Paging, PAE/NX, KVM Paravirtualization
Display
Video Memory: 128 MB
Graphics Controller: VMSVGA
Remote Desktop Server: Disabled
Recording: Disabled
Storage
Controller: IDE
IDE Secondary Device 0: [Optical Drive] Empty
Controller: SATA
SATA Port 0: kali-linux-2025.1a-virtualbox-amd64.vdi (Normal, 80.09 GB)
Audio
Host Driver: Core Audio
Controller: ICH AC97
Network
Adapter 1: Intel PRO/1000 MT Desktop (Internal Network, 'Kali Attacker')
USB


Pfsense router - Settings
Basic
Expert
Search settings
General
System
Display
Storage
Audio
Network
Serial Ports
USB
Shared Folders
User Interface
Network
Adapter 1
Adapter 2
Adapter 3
Adapter 4
Enable Network Adapter
Attached to: NAT
Name:
Adapter Type: Intel PRO/1000 MT Desktop (82540EM)
Promiscuous Mode: Allow VMs
MAC Address: 080027F4360E
Cable Connected
Port Forwarding
Serial Ports
Port 1
Port 2
Port 3
Port 4
Cancel
OK





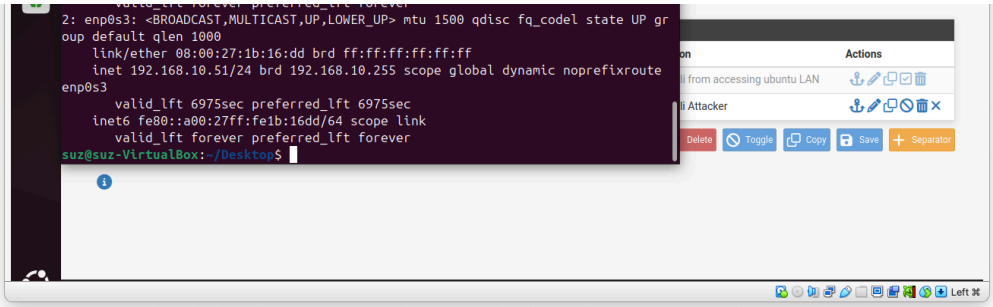
pfSense Interface



9.2 Operating System Network Configuration (DHCP Setup)

• The pfSense DHCP server was enabled on the LAN interface (em1) to dynamically assign IP addresses to devices on the intnet network.
• Ubuntu Server and Ubuntu Desktop were configured to obtain their IP addresses via DHCP:
• Ubuntu Desktop received IP: 192.168.10.51
• Ubuntu Desktop received IP: 192.168.10.50
• The subnet mask is /24, and the default gateway provided via DHCP is 192.168.10.1 (pfSense LAN interface).
• DNS settings were also delivered by pfSense to the Ubuntu machines.

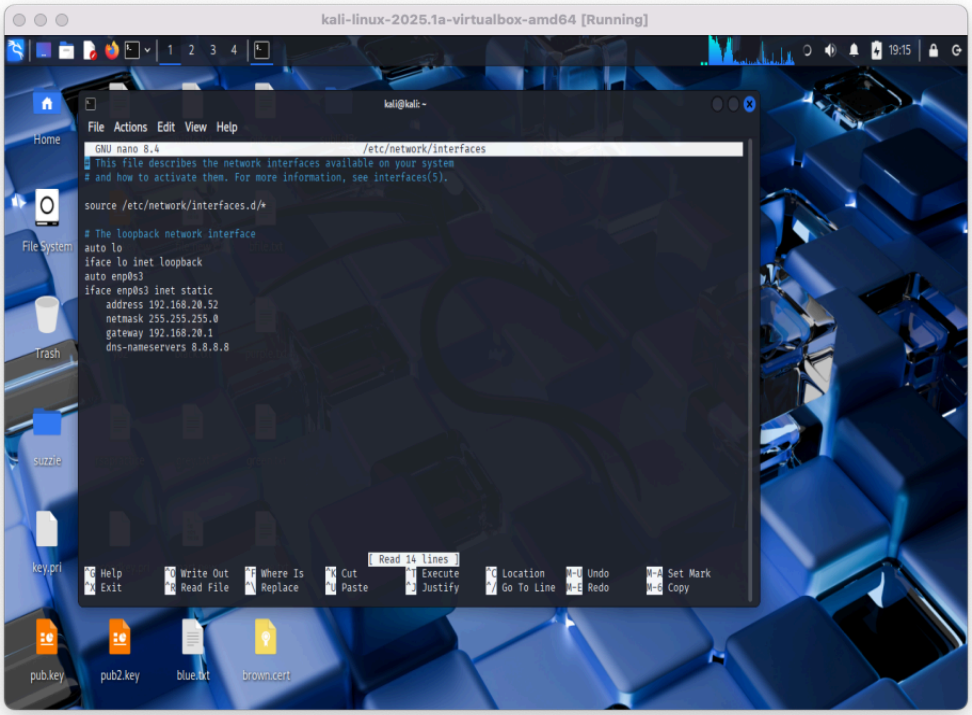
Ubuntu desktop ip



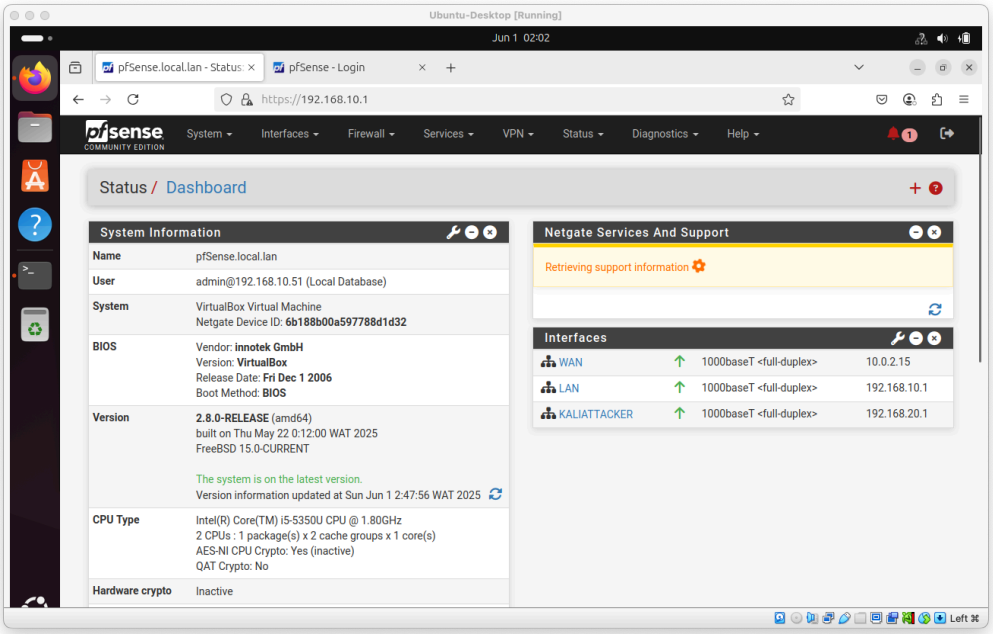
Ubuntu server ip

9.3 pfSense Firewall and Routing Configuration

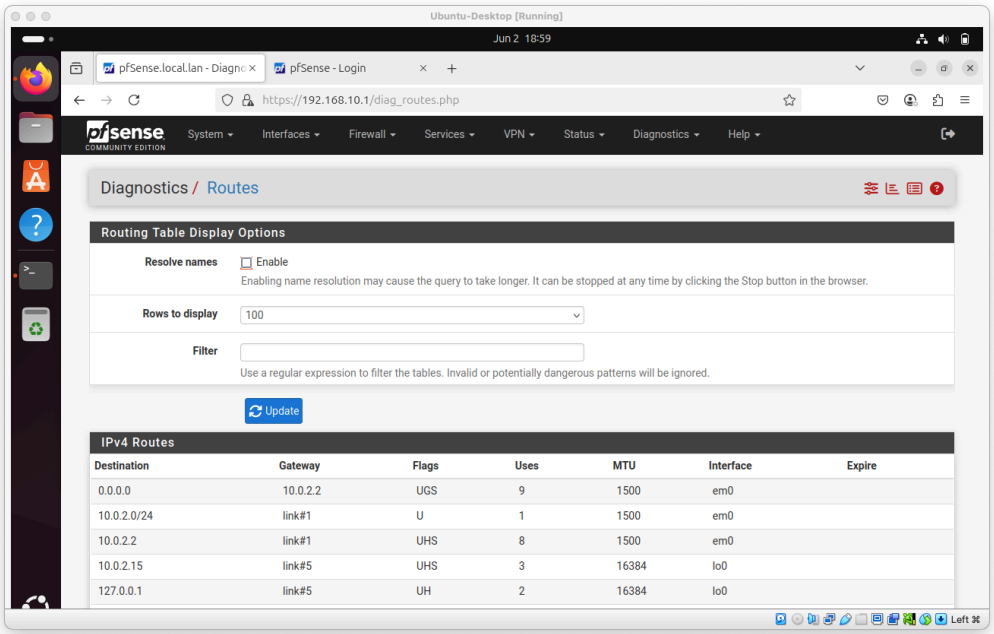
• The WAN interface em0 was configured to receive IP dynamically via NAT from VirtualBox with IP 10.0.2.15.
• The LAN interface em1 was statically set to IP 192.168.10.1 and served as the DHCP server for Ubuntu machines.
• The attacker interface em2 was statically assigned IP 192.168.20.1 for the Kali Attacker network using (sudo nano /etc/network/interfaces)
• Routing and firewall policies were configured to enable controlled communication between networks and isolate the attacker network.



WAN, LAN, and ATTACKER Interface on pfSense GUI



pfSense Routing Table

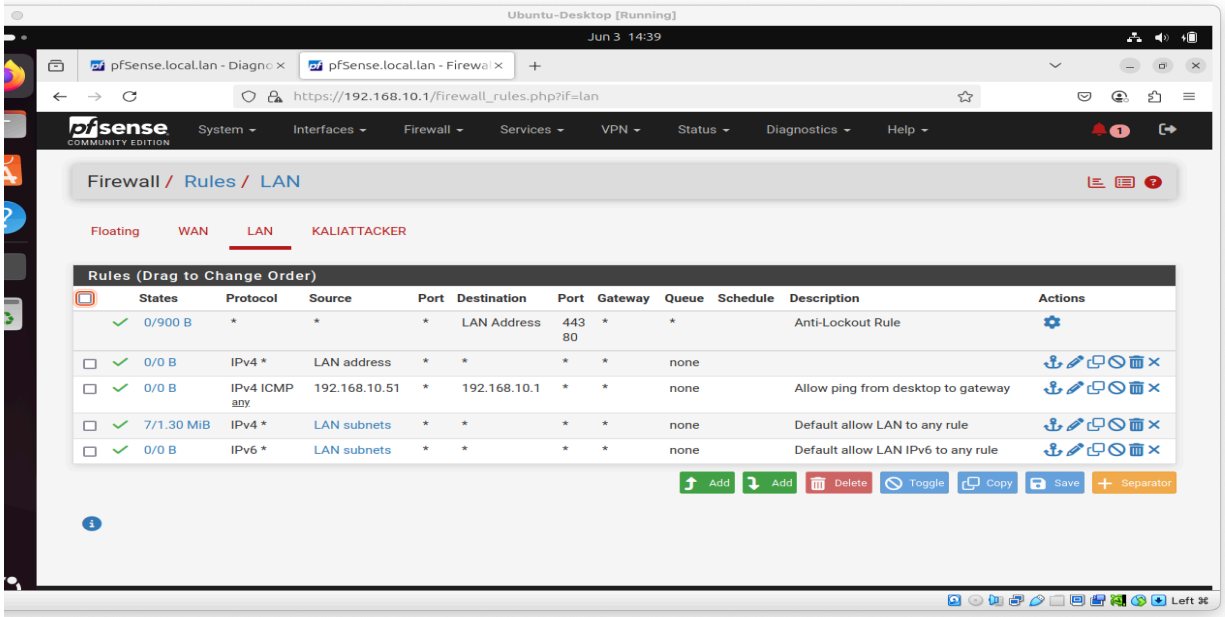


10. Security Controls

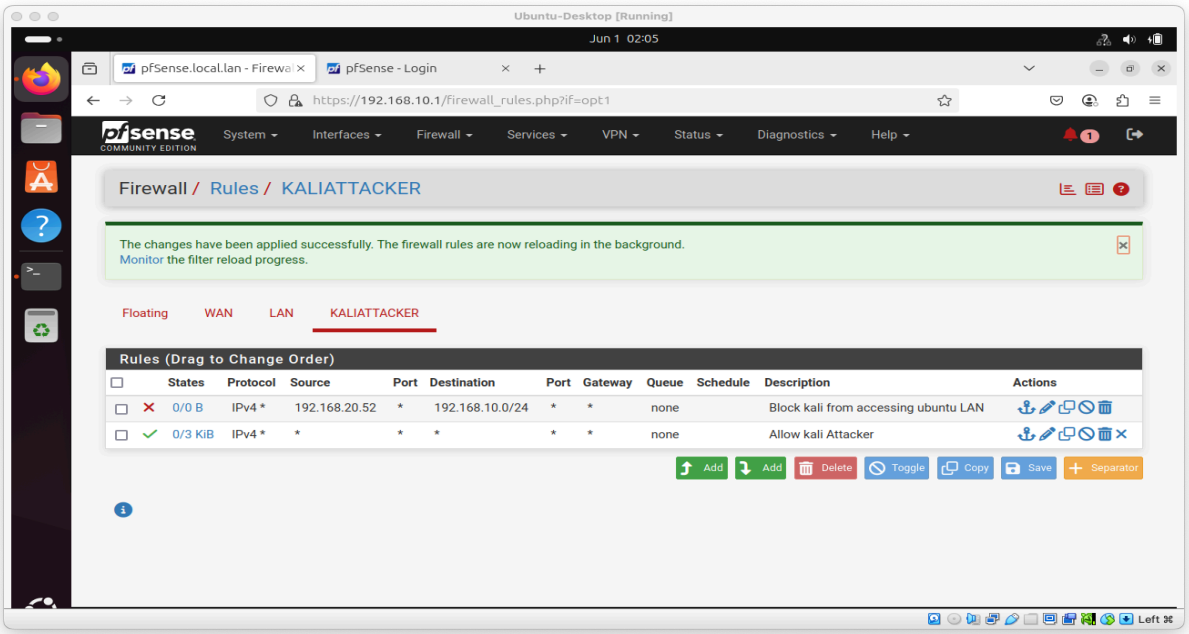
10.1 pfSense Firewall Rules

• Firewall rules on the em2 interface (Kali Attacker) deny all traffic destined for the LAN subnet (192.168.10.0/24), preventing the attacker VM from reaching the internal network.
• Default allow rules were maintained on LAN (em1) to permit normal internal communications.

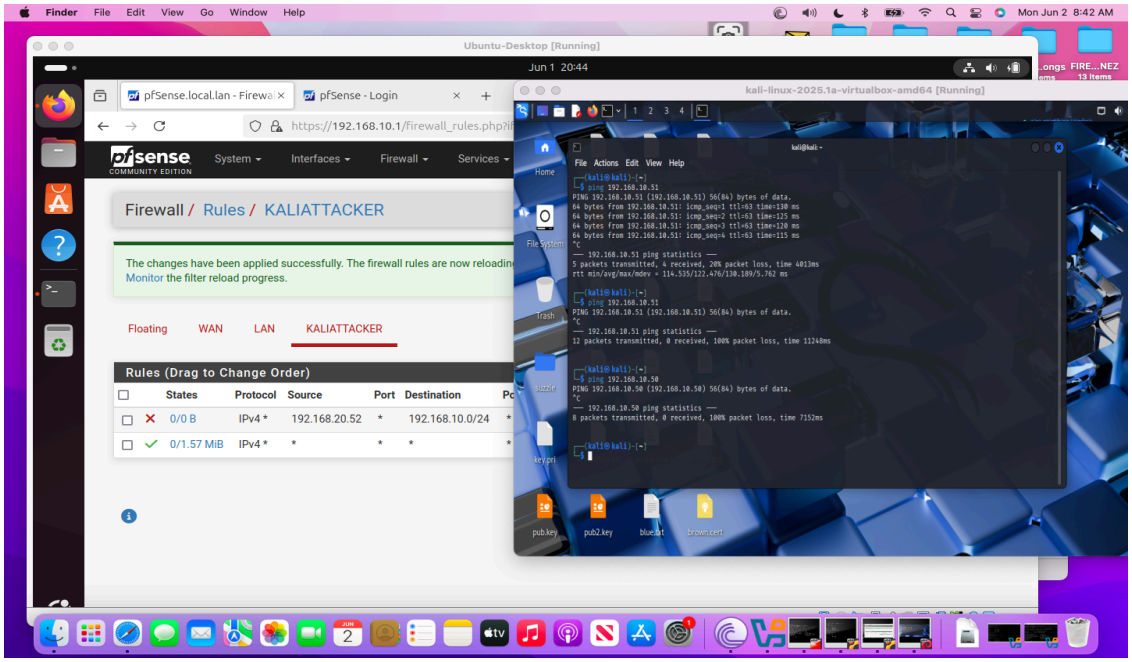
Allow rule on LANs

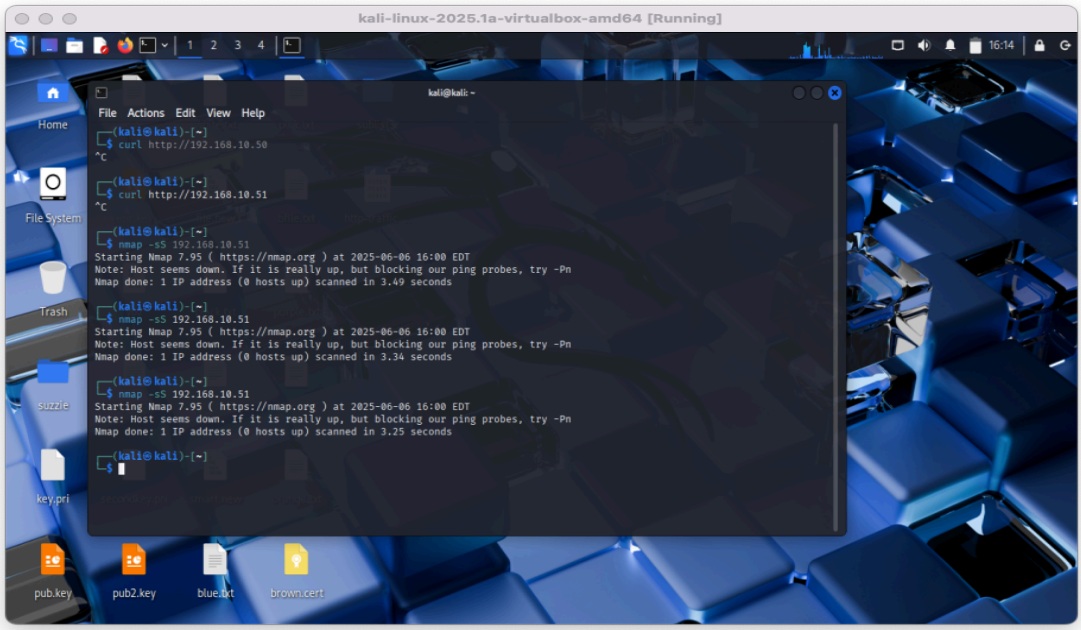


Block rule on Kali enabled



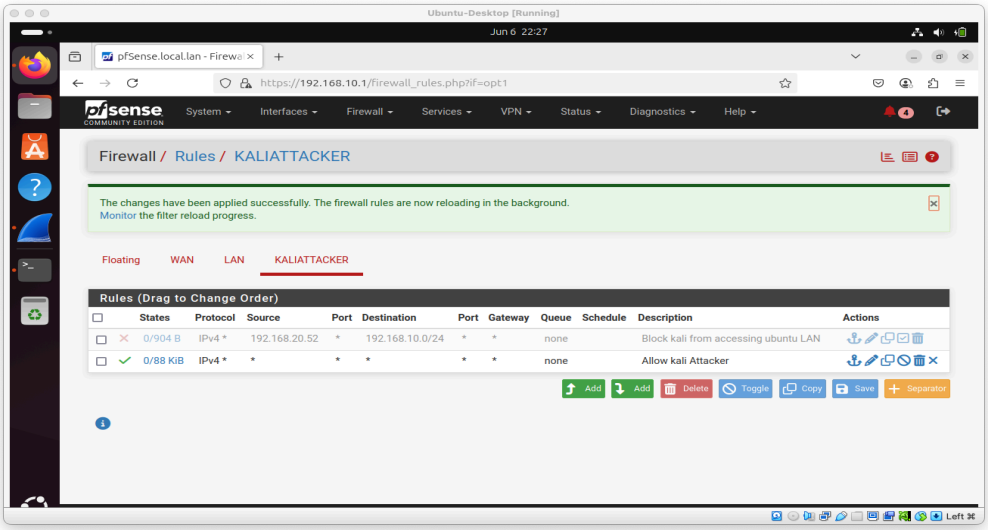
It was observed that wireshark didn’t capture any traffic(HTTP & TCP) when kali was blocked on pfsense, nmap scans reported host to be down. No access at all until It was disabled and we used only UFW rules then traffic could be captured



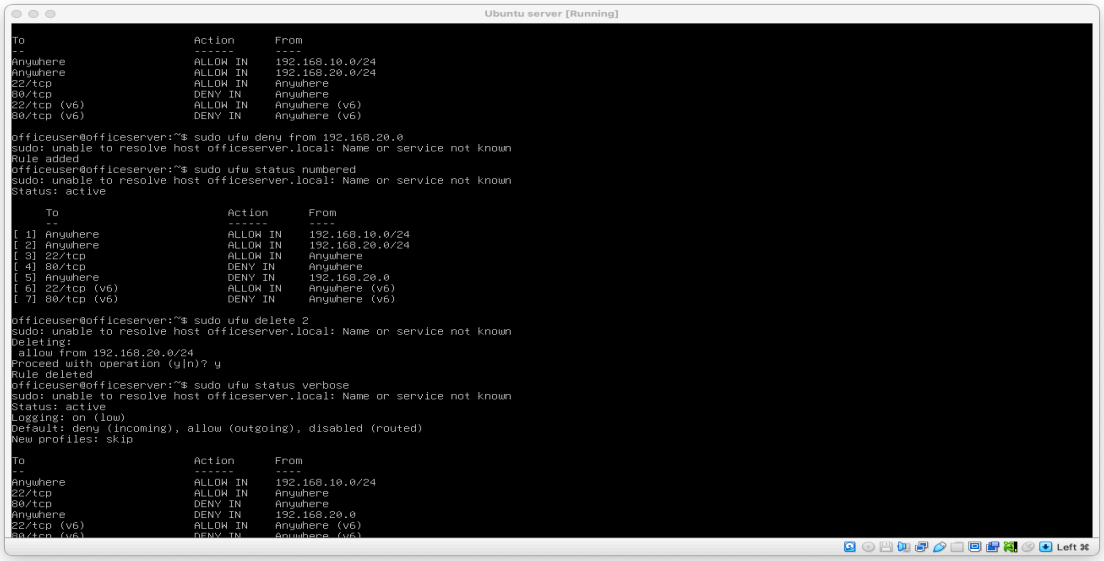


So basically when the firewall is activated on pfsense, traffic does not reach the devices on the LAN so wireshark does not catch it when running wireshark on any of the ubuntus. If UFW rules are set, wireshark will capture it's traffic on the LAN devices. Also, Pfsense log will show it and wireshark on kali too will show it and kali will show it because it is kali sending the requests. So to see wireshark traffic, let us see how UFW

works, so we disabled pfsense



UFW on Ubuntu server



10.2 Host-Based Firewall Configuration (UFW)

• First allowed in all traffic to check connectivity

• Both Ubuntu Server and Ubuntu Desktop enabled UFW with the following policies:

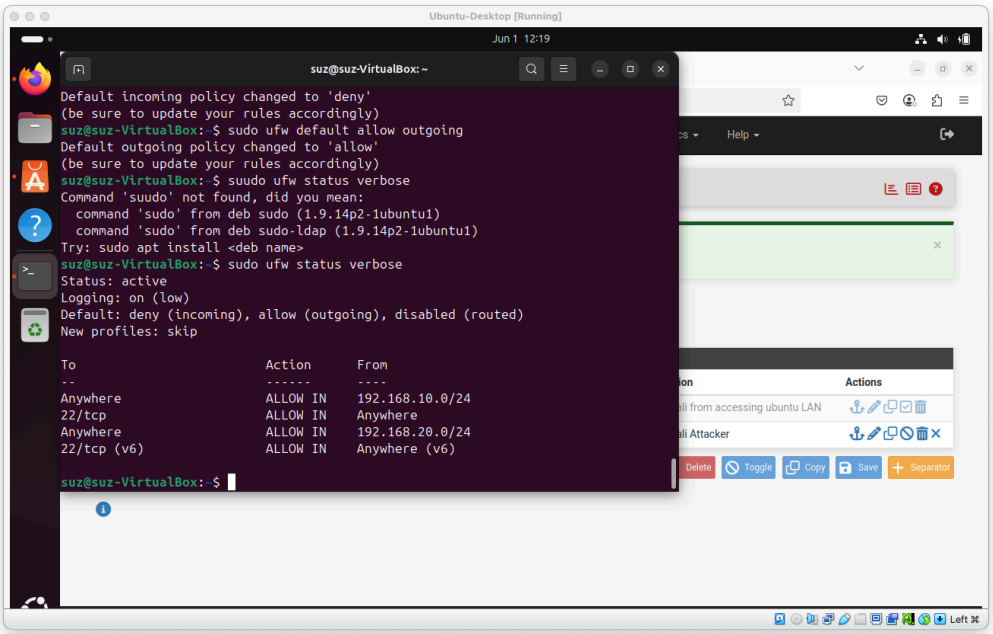
• Default incoming: Deny

• Allow incoming SSH (port 22) only from the LAN subnet (192.168.10.0/24)

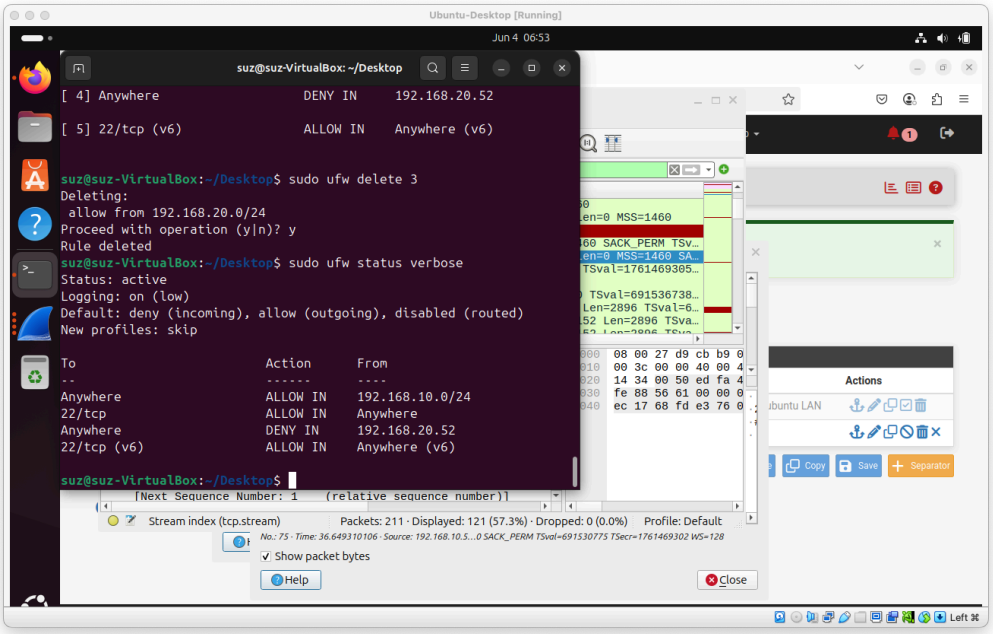
• Allow ICMP (ping) for diagnostics

• Deny all other inbound traffic
• This additional host-level firewall reduced the attack surface and reinforced network security.

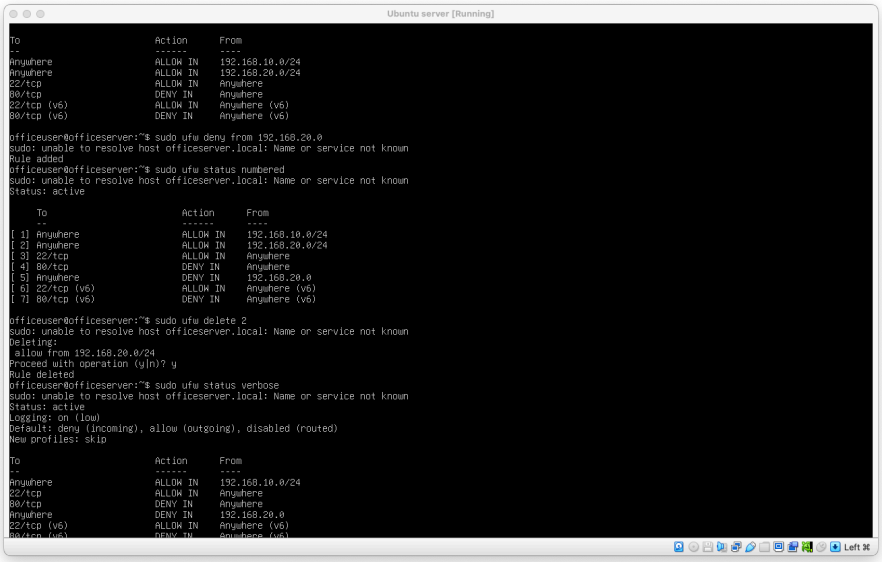
UFW status output on Ubuntu Desktop showing active rules (sudo ufw status verbose) before deny rule



UFW status output on Ubuntu Desktop showing active rules (sudo ufw status verbose) after deny rule



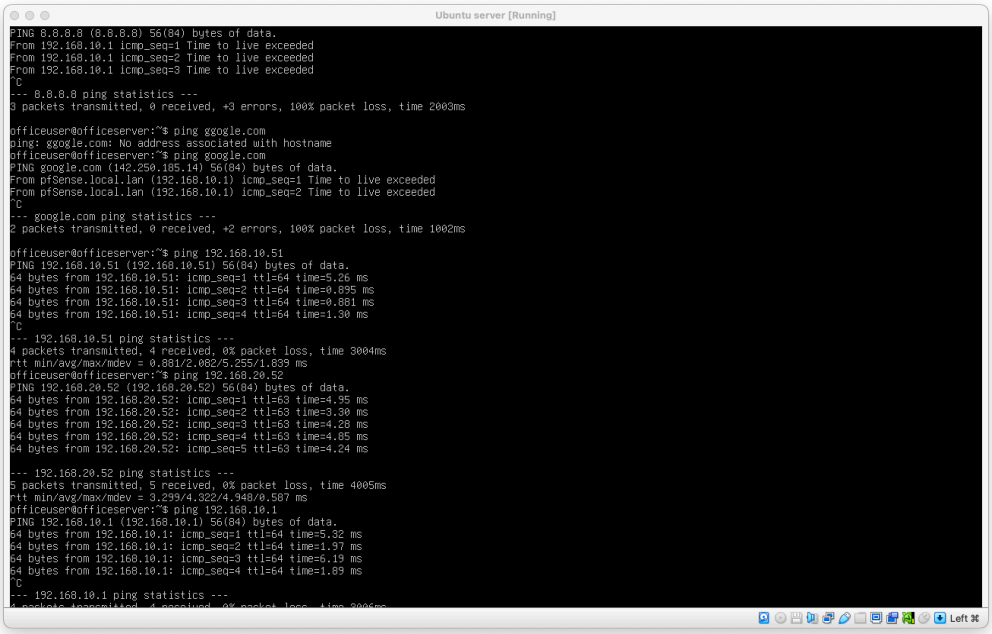
UFW status output on Ubuntu server showing active rules (sudo ufw status verbose) before and after deny rule



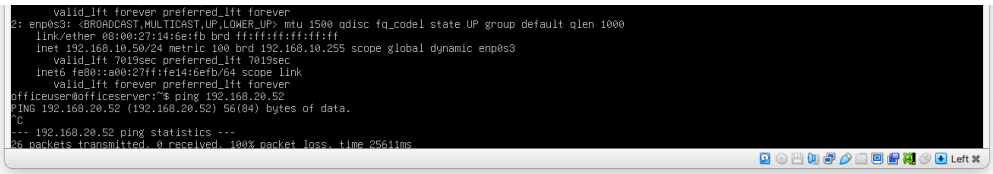
11. Testing and Validation

11.1 Connectivity Testing

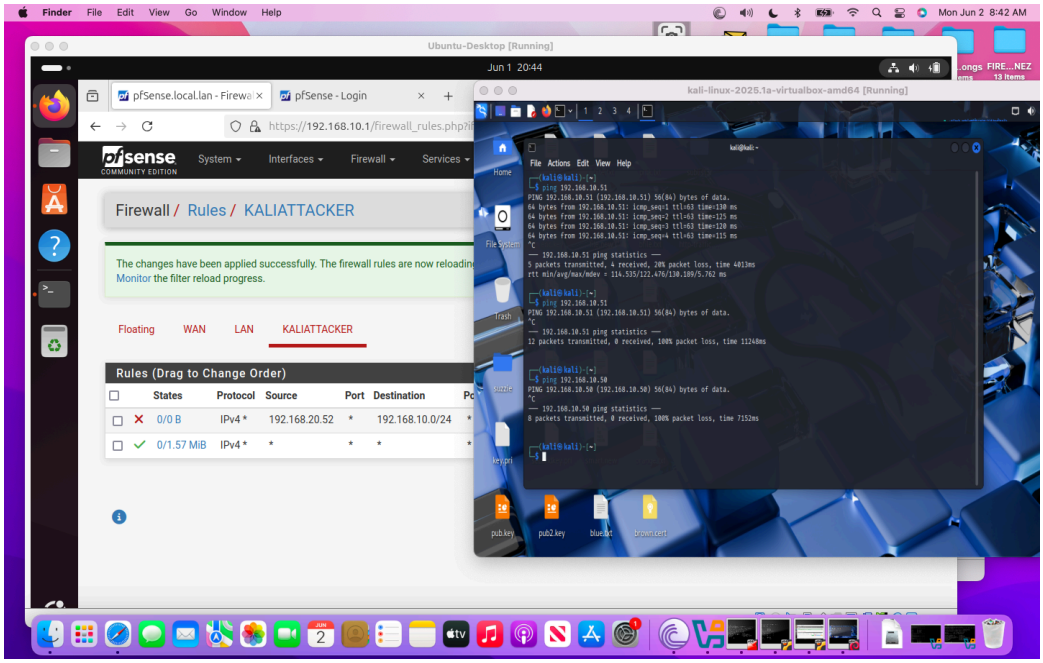
• Ping tests from Ubuntu Server and Desktop to the pfSense LAN interface (192.168.10.1) succeeded, confirming LAN connectivity.
• Ping attempts from Kali Linux (192.168.20.52) to Ubuntu machines (192.168.10.50, 192.168.10.51) went through when the UFW allow rule was set but were later blocked
Successful Ping from Ubuntu Desktop to LAN machines and Kali



Ubuntu server unable to ping KALI ATACKER 192.168.20.52 after block rule added

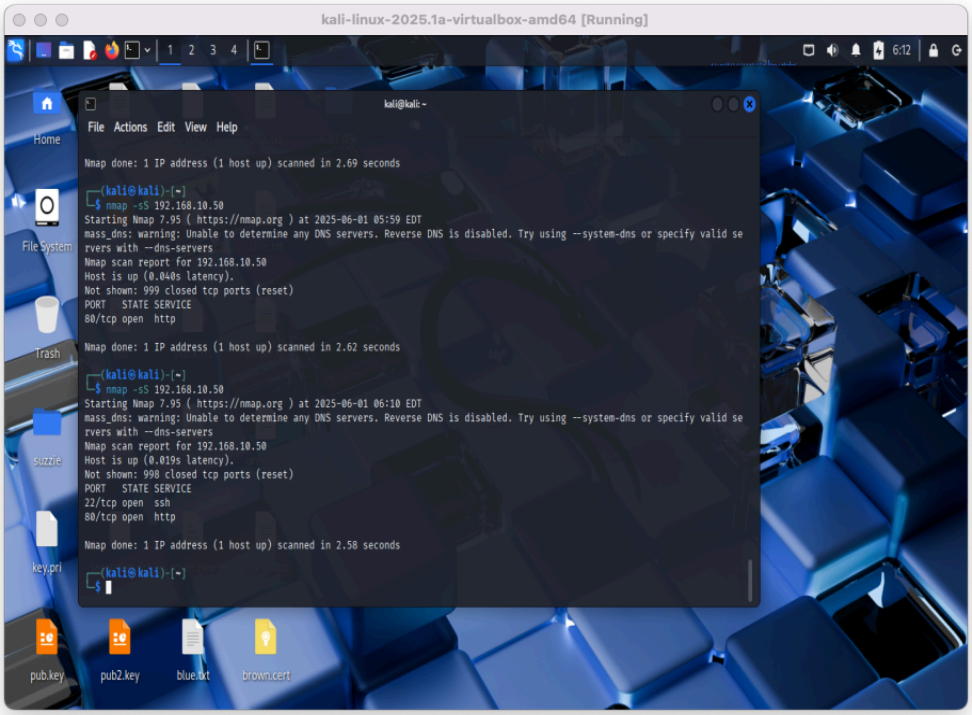


Kali terminal showing ping attempts to Ubuntu server 192.168.10.50 and ubuntu desktop 192.168.10.51 before and after block rule added again



11.2 Network Scanning with Nmap

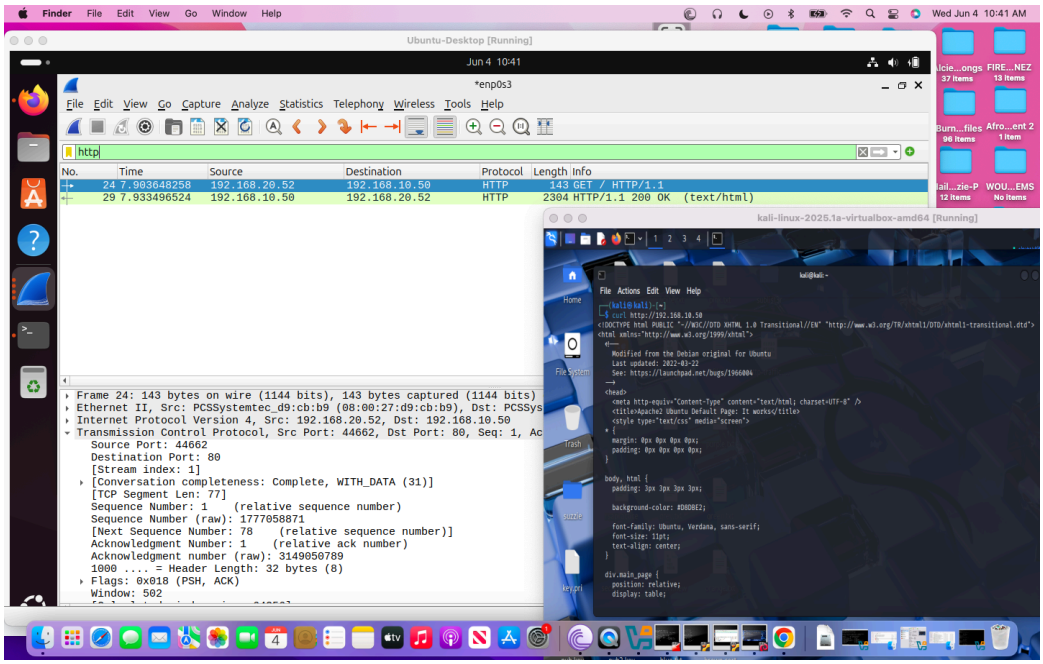
• Kali Linux executed various scans on the Ubuntu machines:
• No open ports were discovered on Ubuntu machines due to effective firewall policies at both pfSense and host level.
• KALI ATTACKER Nmap scan after block rule added
• Had to allow KALI ATTACKER access the LAN machines, also made port 80 and 22 vulnerable on both LAN machines for port scanning using Nmap and network traffic monitoring using Wireshark in the image below:



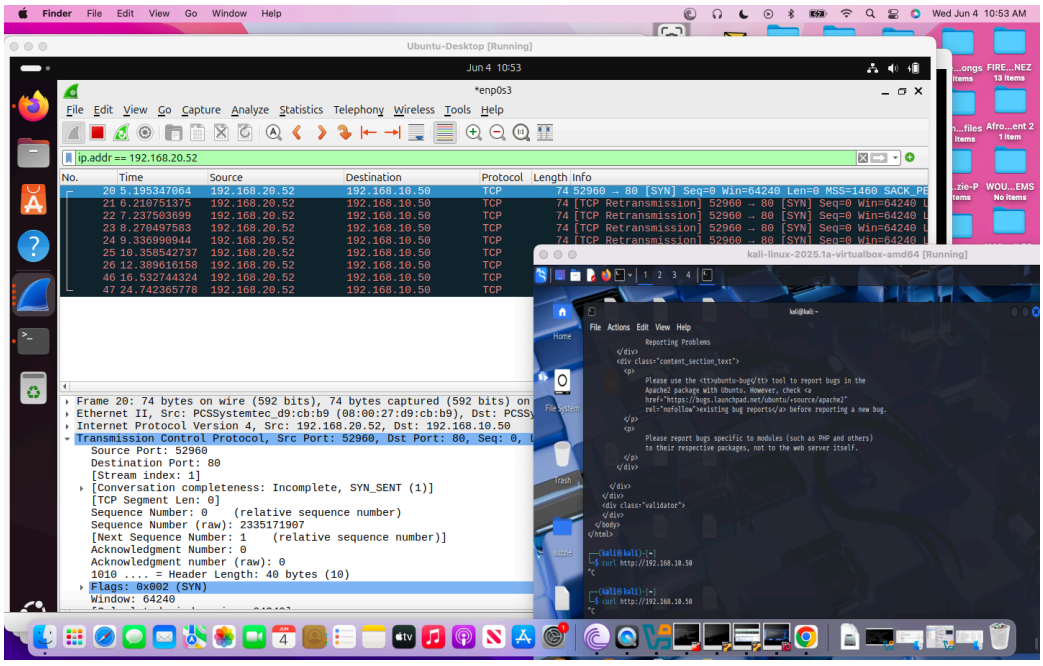
11.3 Traffic Capture and Analysis with Wireshark

• Wireshark running on the Ubuntu Server captured the scan attempts from Kali Linux.
• The captures confirmed that HTTP and TCP connection attempts (SYN packets) from the attacker IP (192.168.20.52) were at first allowed and connected until they were dropped indicating retransmission
• It is important to note that UFW allow rule apply open ports and wireshark captures it as SYN-ACK which means ubuntu server is listening and accepts connection, UFW deny rule apply closed ports and wireshark captures it as RST-ACK, which means ubuntu server actively rejects connection. UFW default deny rule makes ports filtered, so on wireshark it is reported as SYN and no reply which means the server silently dropped packets and they are unresponded to.

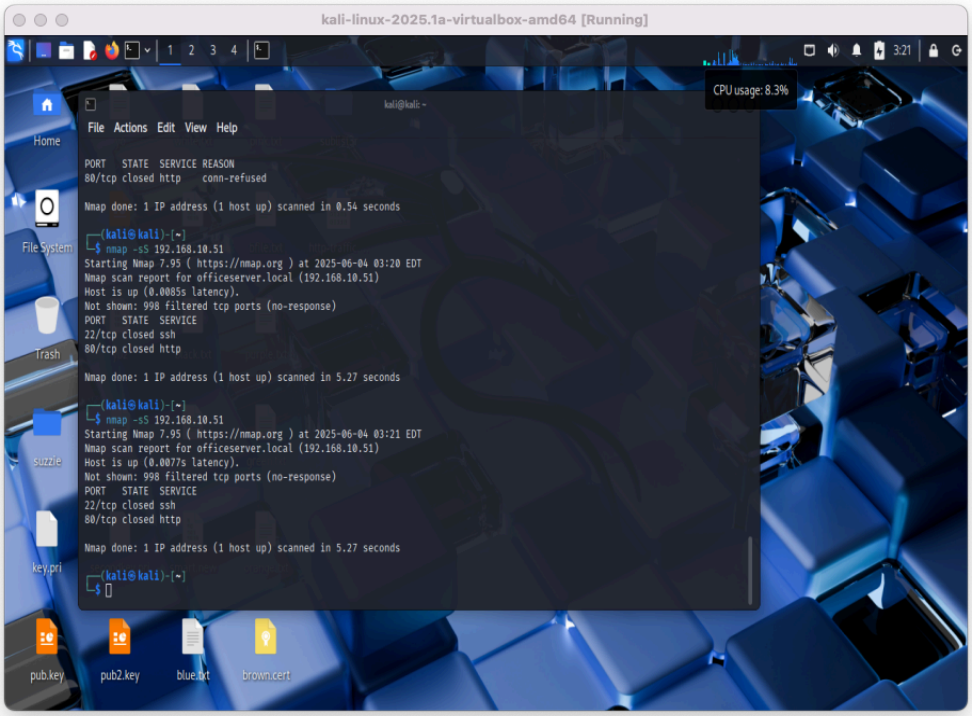
Kali attacker HTTP scan to Ubuntu server before UFW block rule

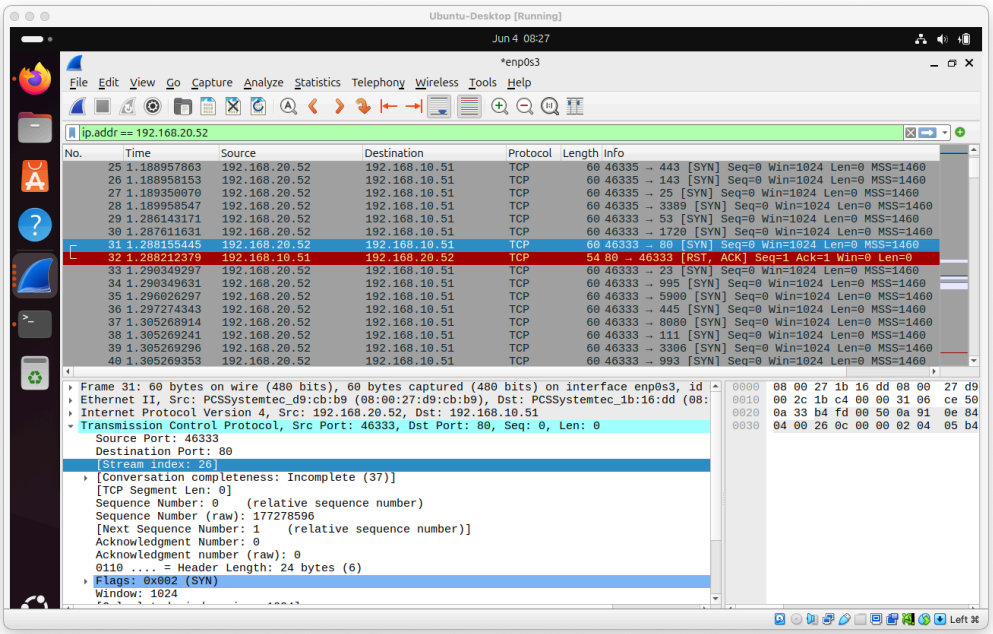


Wireshark HTTP traffic capture showing SYN request blocked, indicating retransmission after UFW deny rule



Kali Nmap scan to ubuntu desktop, wireshark capture on Ubuntu desktop. SSH socket disabled, after which nmap scanned traffic from kali to ubuntu desktop showed port no connection to port 80 (SYN) and traffic blocked on port 22 (RST-ACK) because of hardening even though ping was allowed





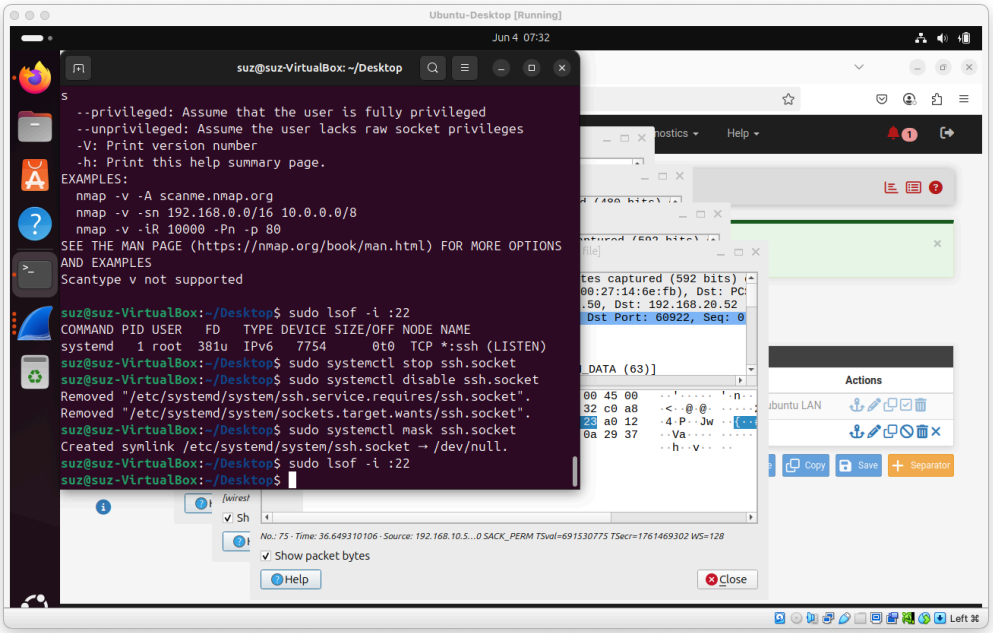
12. Simulated Attack Scenario

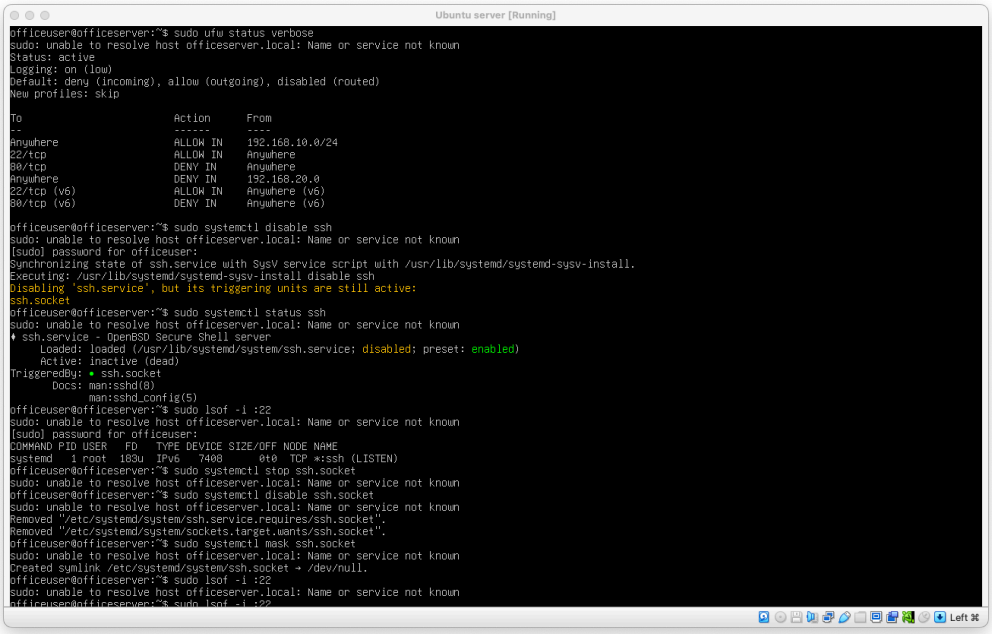
12.1 Attack Description

• Kali Linux simulated an internal reconnaissance attack by scanning and pinging Ubuntu hosts.
• This test emulates a common adversary tactic for network mapping before exploitation.

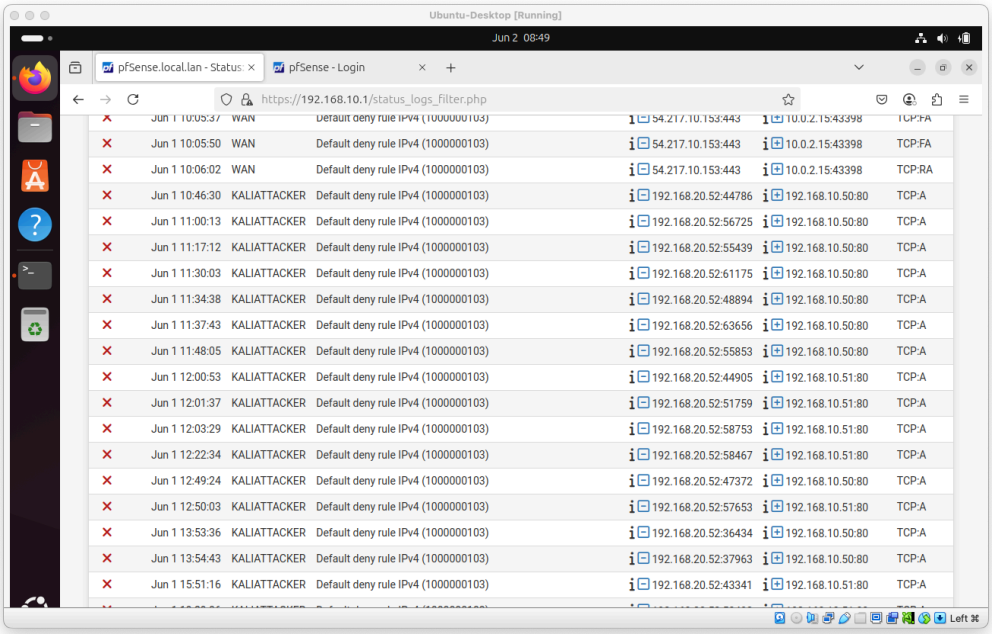
12.2 Defense Outcomes

• Due to network segmentation and firewall rules, Kali's scans revealed no services or open ports on the Ubuntu hosts.
• Ping requests were dropped, confirming strict network isolation.
• Host-based UFW rules added an additional barrier, ensuring no unauthorized access even if firewall rules were bypassed.
• SSH not deactivated on ubuntu desktop and server fully because systemd is still listening and ssh.socket is still active until disabled
• All ports were closed after simulated attack





Logs from pfSense showing blocked traffic entries



13. Results and Discussion

The layered security approach demonstrated effective prevention of unauthorized access from an attacker on a separate subnet. Segmentation via pfSense and host hardening with UFW successfully blocked reconnaissance and lateral movement attempts.
Wireshark analysis provided real-time verification that traffic from Kali Linux was denied access and was unable to interact with Ubuntu machines.
This approach validates the importance of using multiple security layers to mitigate threats in small network environments.

14. Challenges and Lessons Learned

• Properly configuring multiple network interfaces on pfSense was essential for effective segmentation.
• Using DHCP simplified network management and IP assignments but required monitoring to ensure consistent addressing.
• Coordinating firewall rules between pfSense and UFW to avoid conflicts was critical.
• Simulating realistic threats like port scanning and HTTP probing from kali needed controlled testing to avoid noise or false assumption
• Practical testing using real attack tools highlighted the importance of layered security via pfsense (network-level) and UFW (host-level)
• Understanding VirtualBox networking modes (NAT, internal, bridged) was fundamental to network design, planning IP addressing and mapping traffic path is important to avoid connectivity issues.

15. Next Steps and Recommendations

• Explore advanced intrusion detection/prevention systems (IDS/IPS) for enhanced threat detection.
• Implement VPN services for secure remote access to internal network resources.

• Expand the lab to include Windows machines and simulate phishing or malware attacks for broader testing.
• Automate firewall monitoring and logging to improve incident response efficiency.
Conclusion, References, Appendices, and Final Notes

16. Conclusion

This capstone project aimed to design, implement, and secure a small network environment using VirtualBox virtual machines, the pfSense firewall/router, and Ubuntu Linux servers, with Kali Linux serving as an attacker VM on a segregated network.
By assigning three network interfaces to pfSense (em0 as NAT WAN, em1 as LAN intnet, and em2 as Kali Attacker network), the project demonstrated effective network segmentation, isolation, and controlled routing.
Dynamic IP address assignment via pfSense DHCP simplified network management for Ubuntu Server and Desktop while maintaining consistent connectivity within the internal LAN.
Through comprehensive firewall configurations on pfSense and host-based firewalls (UFW) on Ubuntu systems, all unauthorized access attempts and network reconnaissance efforts by the Kali attacker VM were successfully blocked. Testing with ping, nmap scanning, and Wireshark packet analysis validated the implemented security controls.
The layered defense approach implemented is a best practice in network security, providing multiple barriers against potential intrusions, reconnaissance, and lateral movement.
This project highlights the value of combining network segmentation, firewall hardening, and continuous monitoring to secure small and medium-sized networks from internal and external threats.

17. References

• TechCrush Cybersecurity Cohort , March, 2025- Network security, Network protocols, Wireshark, Operating systems by Jeremiah Olubunmi and Faith Olagoke

• pfSense Documentation

Netgate. (n.d.). pfSense Documentation. Retrieved from https://docs.netgate.com/pfsense/en/latest/

• Ubuntu Server Administration

Ubuntu Community. (n.d.). Ubuntu Server Guide. Retrieved from https://help.ubuntu.com/lts/serverguide/

• Ubuntu UFW Firewall

Ubuntu Community Help Wiki. (n.d.). UFW - Uncomplicated Firewall. Retrieved from https://help.ubuntu.com/community/UFW

• Nmap Network Scanning

Lyon, G. F. (2009). Nmap Network Scanning: The Official Nmap Project Guide to Network Discovery and Security Scanning. Insecure.Com LLC.

• Wireshark User Guide

Combs, G. (n.d.). Wireshark User's Guide. Retrieved from https://www.wireshark.org/docs/wsug_html_chunked/

• VirtualBox Networking

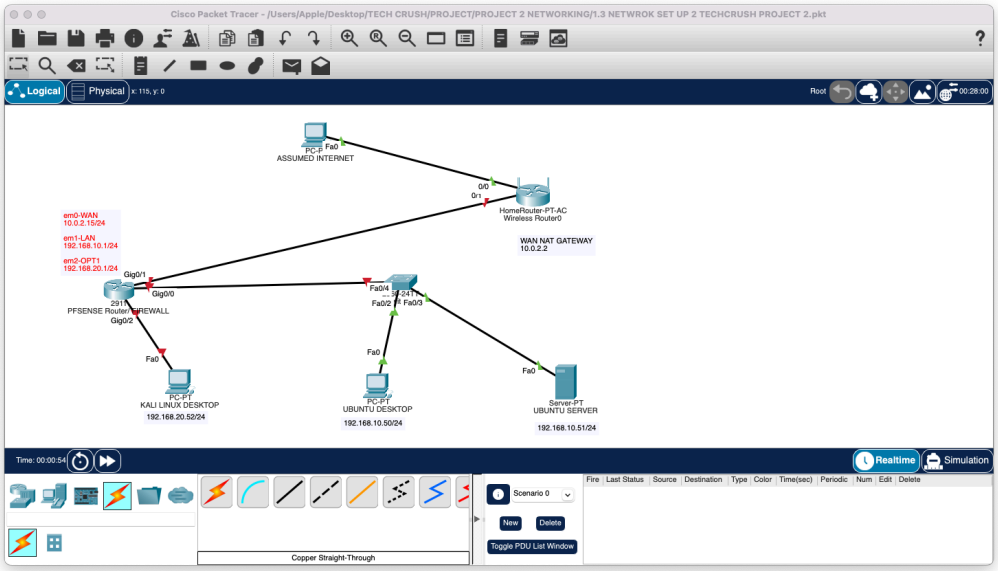
Oracle. (n.d.). VirtualBox User Manual. Retrieved from https://www.virtualbox.org/manual/ch06.html

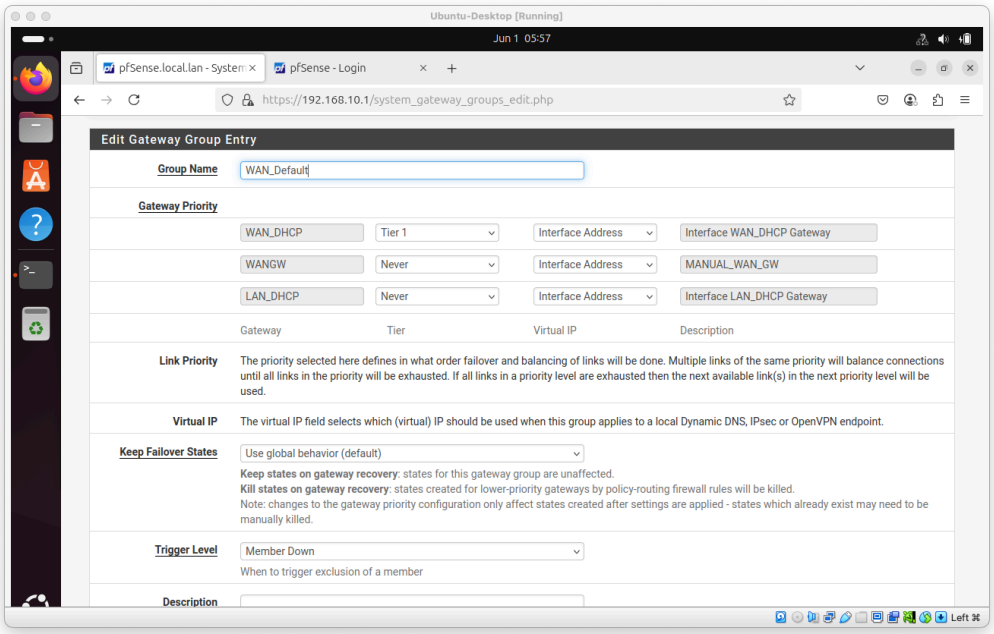
• General Cybersecurity Principles

Stallings, W. (2018). Network Security Essentials: Applications and Standards (6th ed.). Pearson.

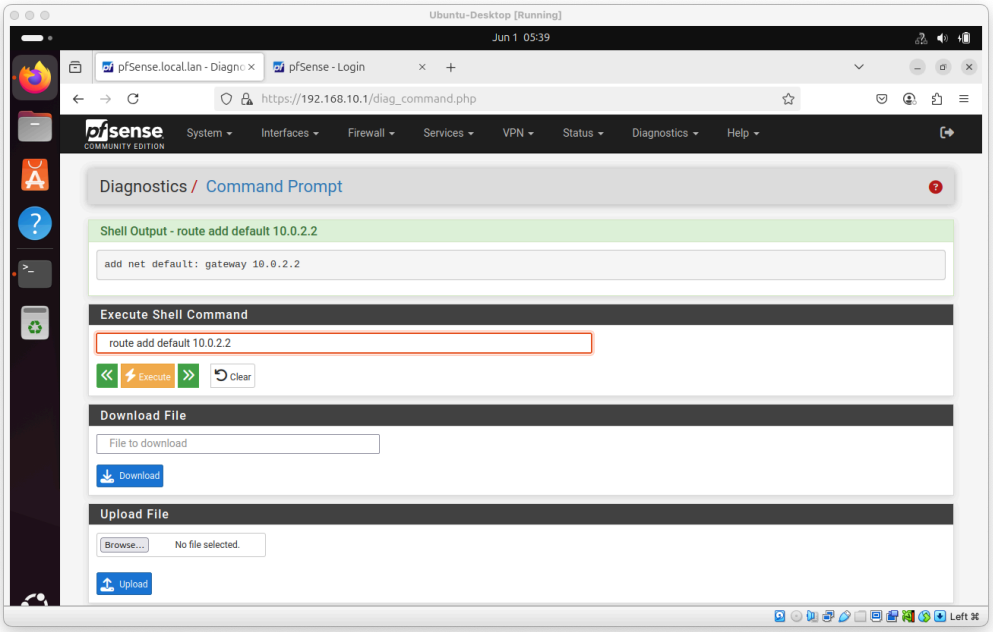
18. Appendices

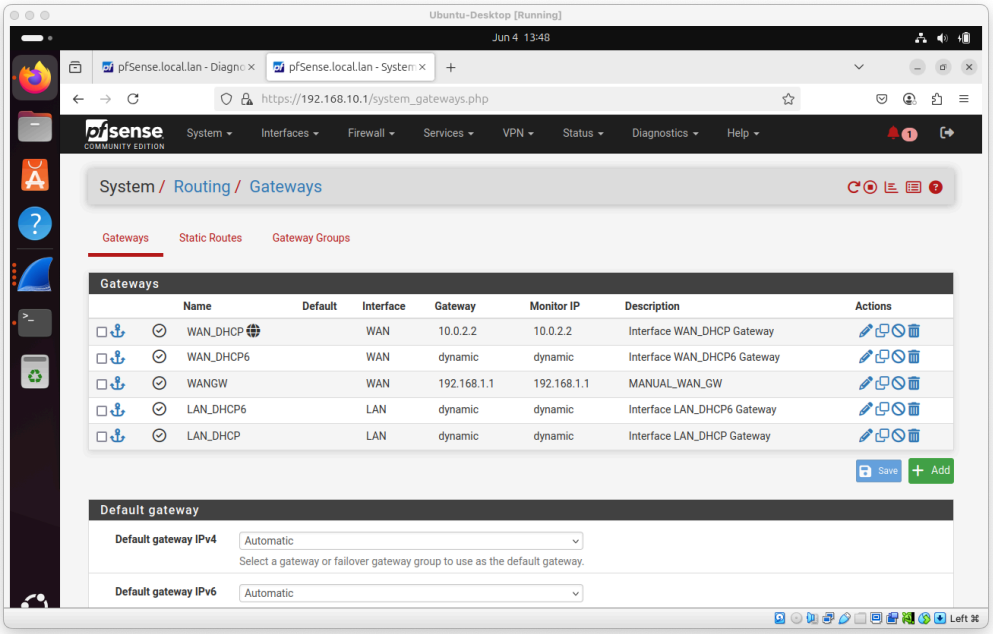
Configuration Files and Command Outputs

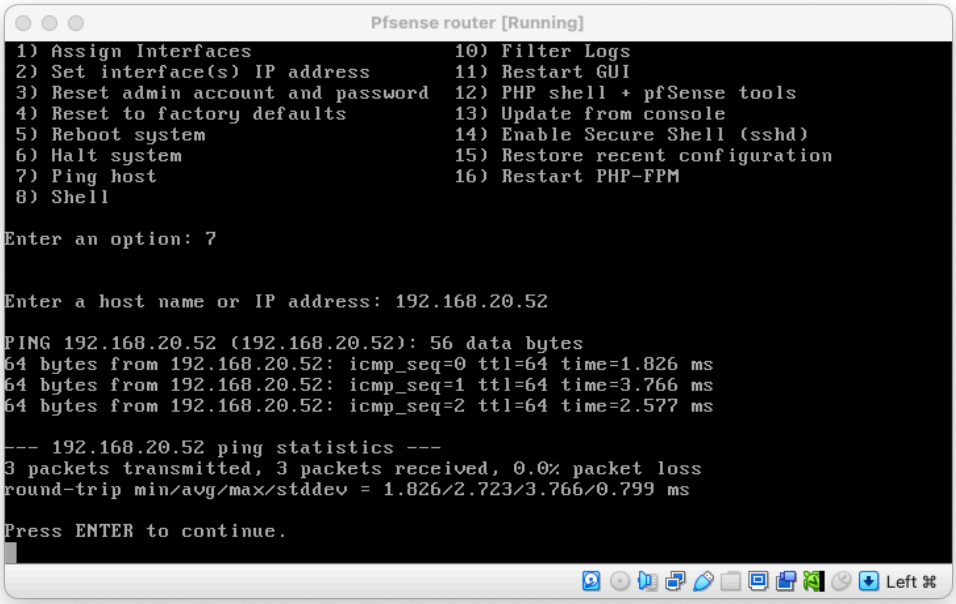


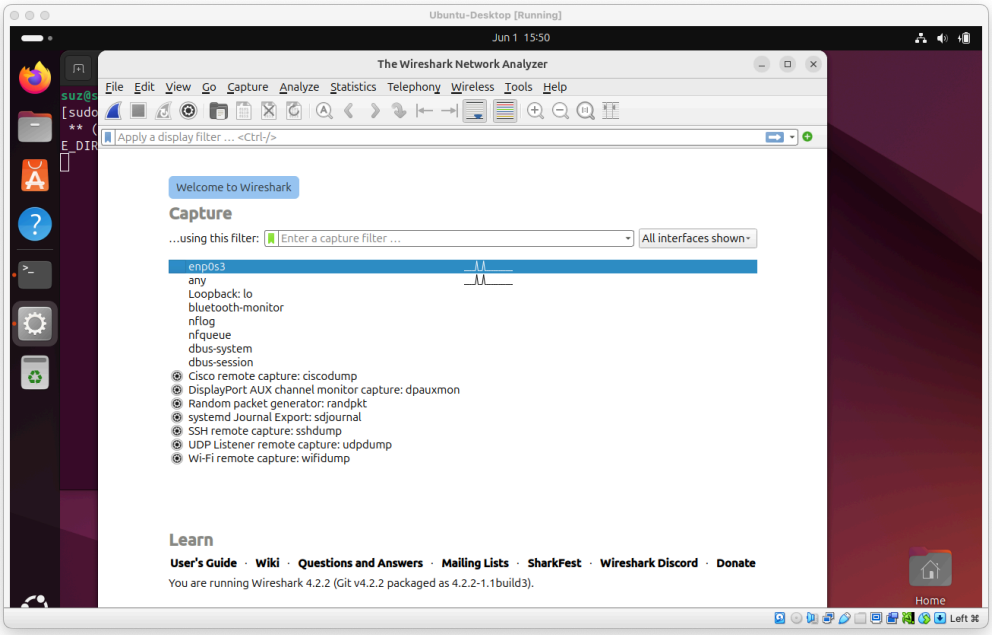


Static gateway added at first on pfsense via system/routing/gateway, checked the box for WAN DHCP and applied changes then it was permanent.






Pfsense router [Running]
1) Assign Interfaces
2) Set interface(s) IP address
3) Reset admin account and password
4) Reset to factory defaults
5) Reboot system
6) Halt system
7) Ping host
8) Shell
10) Filter Logs
11) Restart GUI
12) PHP shell + pfSense tools
13) Update from console
14) Enable Secure Shell (sshd)
15) Restore recent configuration
16) Restart PHP-FPM
Enter an option: 7
Enter a host name or IP address: 192.168.20.52
PING 192.168.20.52 (192.168.20.52): 56 data bytes
64 bytes from 192.168.20.52: icmp_seq=0 ttl=64 time=1.826 ms
64 bytes from 192.168.20.52: icmp_seq=1 ttl=64 time=3.766 ms
64 bytes from 192.168.20.52: icmp_seq=2 ttl=64 time=2.577 ms
--- 192.168.20.52 ping statistics ---
3 packets transmitted, 3 packets received, 0.0% packet loss
round-trip min/avg/max/stddev = 1.826/2.723/3.766/0.799 ms
Press ENTER to continue.
Left ⌘


Ubuntu-Desktop [Running]
Jun 1 15:50
The Wireshark Network Analyzer
File Edit View Go Capture Analyze Statistics Telephony Wireless Tools Help
Apply a display filter ... <Ctrl-/>
Welcome to Wireshark
Capture
...using this filter: Enter a capture filter ...
All interfaces shown
enp0s3
any
Loopback: lo
bluetooth-monitor
nflog
nfqueue
dbus-system
dbus-session
Cisco remote capture: ciscodump
DisplayPort AUX channel monitor capture: dpauxmon
Random packet generator: randpkt
systemd Journal Export: sdjournal
SSH remote capture: sshdump
UDP Listener remote capture: udpdump
Wi-Fi remote capture: wifidump
Learn
User's Guide · Wiki · Questions and Answers · Mailing Lists · SharkFest · Wireshark Discord · Donate
You are running Wireshark 4.2.2 (Git v4.2.2 packaged as 4.2.2-1.1build3).
Home
Left ⌘