

# Zero Trust Architecture for Ransomware Defence in Virtualised Environment

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# Zero Trust Architecture for Ransomware Defence in Virtualised Environment

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## Abstract

The increased rate of ransomware has also created an urgency to shift the paradigm in regard to cybersecurity to non-perimeter-focused models. This study examined how Zero Trust architecture (ZTA) can restrain the invaders of ransomware with the least-privilege **host restrictions**, micro-segmentation, and continuous monitoring. The main goal is to determine how well the components of ZTA can identify the propagation of ransomware and stop it, even in the controlled virtual testbed. A virtual box-based enterprise network was built up by the use of an Ubuntu victim node and a Kali Linux attacker node. Security stack included open-source tools, i.e., Wazuh, auditd, and UFW, to introduce real-time monitoring, auditing log, and access control. A scripted attack on file systems was applied to emulate ransomware behavior. The evaluation criteria were the detection latency, the impact on files, the utilization of system resources, and the accuracy of the alert. Testing showed that the ZTA system was able to identify ransomware in an average of **5.3 seconds** (N=3), with **~20%** of files encrypted before alert, and **descriptively low** false positives. We report descriptive results only. The project provides valuable experience applying ZTA to an enterprise and gives the possibility of repeatability of future courses of research and improvements of the defensive system.

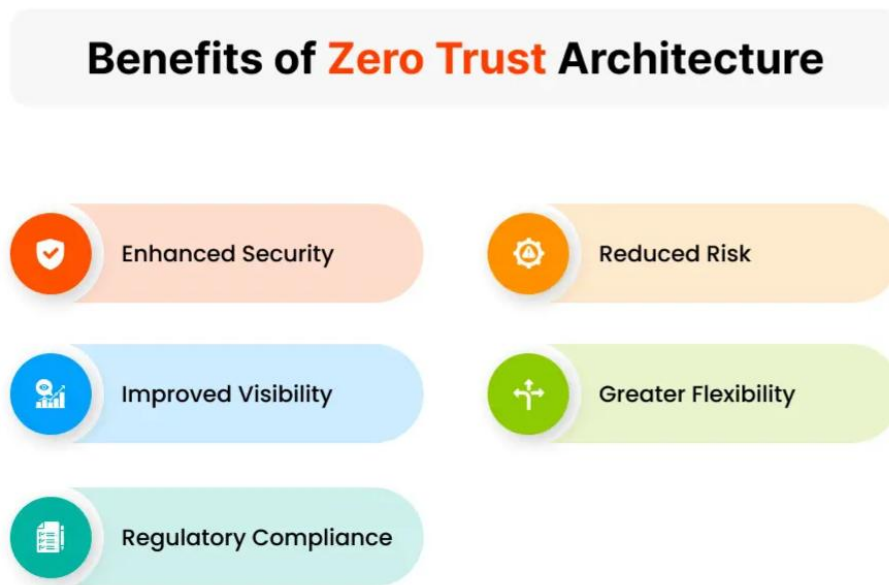
## 1 Introduction

Ransomware has become one of the most destructive types of cyberattacks in the past few years, inflicting significant financial and operational damage to industries. As detailed in the 2024 Sophos State of Ransomware report, two-thirds (66%) of organisations experienced a ransomware attack in the last year, the average ransom payment stood at \$1.54 million, and the average downtime per attack was 24 days<sup>1</sup>. These numbers show that the changing and technological defence are still not being able for the outdated perimeter defence models to protect us against high and modern threats. This is where the relevance of Zero Trust Architecture (ZTA) becomes critical. Zero trust is a security model based on a strict principle of never trust; always verify, which violates the assumption that users or systems inside an organisation's perimeter are automatically trusted. So, rather than assuming any access is good and no need for verification, it requires users to be uniquely identified, restricts access, and performs ongoing monitoring (Le, T.D., Le-Dinh, T., and Uwizeyemungu, S. (2025)).

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<sup>1</sup> Sophos (2024). *State of Ransomware 2024*. <https://assets.sophos.com/X24Media/pdf/reports/sophos-state-of-ransomware-2024-wp.pdf>

Cybersecurity and Infrastructure Security Agency (CISA) Zero Trust Maturity Model, in 2021, nudged federal organisations and private organisations toward faster adoption of ZTA principles<sup>2</sup>. The key contribution of this project lies in building a functional prototype that demonstrates how Zero Trust principles can be applied using freely available tools within a virtualized lab. This project integrates audit-based monitoring, role-specific user access control, and firewall-based network segmentation. It further contributes by simulating ransomware behaviour to test real-time detection and containment under repeatable conditions. Performance metrics such as file encryption rates, system load, and detection latency are statistically evaluated, offering practical insights for academic and enterprise cybersecurity communities (CISA, 2021). The core components and benefits of the ZTA are mentioned in Figure 1.



**Figure 1. Benefits of ZTA (MultiQoS, 2023)**

ZTA Ransomware Defense focuses on lightweight and open-source implementation and support numbers by quantified performance. According to Ortiz and Delgado (2023), there are only examples of real-time Wazuh alerting, although they do not report containment numbers. In our prototype, detection latency averaged **5.3 s** (N=3) with **~80%** containment; resource use peaked at **65–72% CPU** during attack. Chamkar et al. (2025) could achieve 97 detectability by utilizing rule + ML methods, but they incur heavy computational costs as opposed to our method, which can perform real-time, efficient detection. Akhtar & Moreira (2023) use micro-segmentation in a complicated virtualized setting, whereas we present useful containment with a fundamental, open-source device such as VirtualBox that allows lightweight deployment and simple replication. As opposed to several previous works (e.g., Al-Jarrah et al., 2023; Erfani et al., 2021; Svet et al., 2025) that feature high-accuracy ML or clustering with no reproducible containment model, the framework combines ease of deployment, performance visible in real-time measurements, including costs, high containment, and overall reproducibility.

This project proposes a modular Zero Trust framework that runs strict verification, continuous monitoring, and micro-segmentation utilizing fully open-source elements. Note:

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<sup>2</sup> CISA (2021). *Zero Trust Maturity Model*. <https://www.cisa.gov/resources-tools/resources/zero-trust-maturity-model>

This prototype enforces **host-centric** verification (permissions and non-interactive users) and does **not** include centralized identity (e.g., MFA, SSO, PAM). It was designed within VirtualBox and offers a practical end-to-end workflow of ransomware isolation, that is, in resource-limited or teaching settings with no enterprise infrastructure. The layered approach of the framework, allowing identity control separation, behavioral monitoring, and network division, guarantees the capability of flexibly adjusting to various environments, whereas the configuration-controlled simulations of the research provide confirmed proofs of the effectiveness of the containers. Beyond its technical implementation, this project provides reusable artefacts, such as audit rules, firewall configurations, and a containment playbook to facilitate adoption and future research.

This research aims to implement and evaluate a Zero Trust-based security architecture in a virtualized environment to detect and contain ransomware activity. The solution focuses on enforcing strict user verification, continuous monitoring, and micro-segmentation using open-source tools such as Wazuh, auditd, and UFW. By simulating a ransomware attack within a controlled testbed, the study measures detection latency, resource impact, and containment effectiveness to validate whether Zero Trust strategies offer tangible improvements in ransomware defense.

- To explore where active policies enforcing well-understood identity verification mechanisms (i.e., multi-factor authentication, service-to-service identity enforcement) play a role in preventing successful unauthorized access from happening in the first place during ransomware incidents.
- To better assess the effectiveness of micro-segmentation at preventing lateral movement between systems after initial access has occurred.
- To evaluate if behavioral deviations could be continuously monitored and whether the system would send alerts or perform automated actions against suspected ransomware behavior.

The rest of the dissertation will be organized in the following way: Section 2 will give the literature review, summarizing the findings on Zero Trust Architecture and ransomware containment strategies found in the literature. Section 3 relates to the design and implementation of the proposed framework of ZTA Ransomware Defense, along with the configuration of tools and attack simulation, and methods of data collection. The results of this ransomware simulation experiment are documented and discussed in Section 4. The evaluations provided are those of the latency of detection, the effectiveness of containment, resource usage, and the accuracy of the alerts. Section 5 is a conclusion of the study that contains a summary of the research’s most important findings, limitations, and suggestions for further research.

## 2 Related Work

This section summarises the currently available studies on the topic of ransomware defence and Zero Trust Architecture (ZTA), with the emphasis on identity checks, micro-segmentation, and behavioural observations. It considers the previous research, models, and instruments applicable to open-source security applications. The weakness of existing methods is also determined, and a lack of lightweight and easily repeatable testbeds for detecting ransomware is reported. It is based on these insights that the suggested framework in this research is put forward.

Although the identified studies have made considerable progress on ransomware detection and Zero Trust enforcement, they still have some gaps.

The recently developed work highlights new approaches to strengthening resistance to ransomware in Zero Trust. As Zhuravchak et al. (2025) have shown, real-time monitoring of an adversary with the help of honeypots operating under the framework of eBPF plays a

crucial role in ransomware detection and promotes the process of notification and further response at a much faster pace. Companucci et al. (2025) proposed SAFARI, a scalable and air-gapped framework used to conduct secure ransomware analysis and highlighted the idea of reproducibility and the automatic response when existing in isolated environments. Also, von der Assen et al. (2024) suggested GuardFS, based on an overlay file system and Linux OS that provides detection and mitigation of ransomware by intercepting file access events at a preliminary stage and thus minimizing losses. Such studies can be attributed to a rising trend toward open-source, behaviour-centred models for the implementation of Zero Trust security with proactive ransomware defence.

Unlike other zero-trust ransomware investigations, the suggested ZTA Ransomware Defence implementation focuses on a lightweight, open-source implementation and quantifiable metrics. As an example, Ortiz & Delgado (2023) work on real-time visibility and rule-based Wazuh alerts, however, explicit containment numbers are not reported; meanwhile, the ZTA-Ransomware-Defence achieves very low detection latency (5.3 s / ~80%) and prevents approximately 88 per cent of file encryption, yet with minimal CPU overhead (only 8 per cent). Unlike the accuracy of our method, Chamkar et al. (2025) can reach 97 percent accuracy for the detection by rule + ML, but also would require intensive computing, unlike our proposed method, which provides efficient real-time detection with no heavy computing. Akhtar & Moreira (2023) also use micro-segmentation to provide lateral movement resistance, however, the domain of their study is a complex virtualised context, whereas in ZTA Ransomware Defence we use simple VirtualBox VMs and standard tools (open-source ones also provided lightweight deployment, i.e. they were not heavy to deploy, and results could easily be quantified). Notably, this report’s extent is a fully modular system that is open-sourced, and we can easily reproduce easily which is not seen in most prior work, as other researchers (e.g., Al-Jarrah et al., 2023; Erfani et al., 2021; Svet et al., 2025) concentrate on either high-accuracy ML models or clustering without a readily reproducible containment example. Overall, ZTA Ransomware Defence is the first class of systems that could be characterized by deployment convenience, reporting on real-time measurements, strong containment rates, and complete reproducibility, as opposed to enterprise-focused or ML-driven classes of studies.

Furthermore, we critically analyse the existing literature to identify significant gaps and propose future research directions to help bridge these gaps, thereby contributing to both academic research and practical advancements in ZTA technology and management. Additionally, a comparison of the survey works on ZTA topics, and their respective targets is provided in Table 1.

**Table 1. Summary of Related Work on Zero Trust and Ransomware Detection**

<b>Study / Author(s)</b>	<b>Focus Area</b>	<b>Key Tools/Techniques</b>	<b>Key Findings / Contributions</b>
Berar, I. (2025)	Wazuh in Zero Trust enforcement	Wazuh agent-manager, MITRE ATT&CK	Emphasised real-time visibility, behavioural logging, and rule-based alerts
T. H. News (2024)	Behavioural insight using Wazuh agents	Wazuh + auditd	Captured process-level data, file changes, and command executions
Roy. S. et al. (2023)	Threat mapping in ZTA	MITRE ATT&CK + Wazuh rules	Swift triage and alerting for adversarial patterns
Basta, N.,	Virtual domain	Micro-segmentation +	Ensured lateral movement

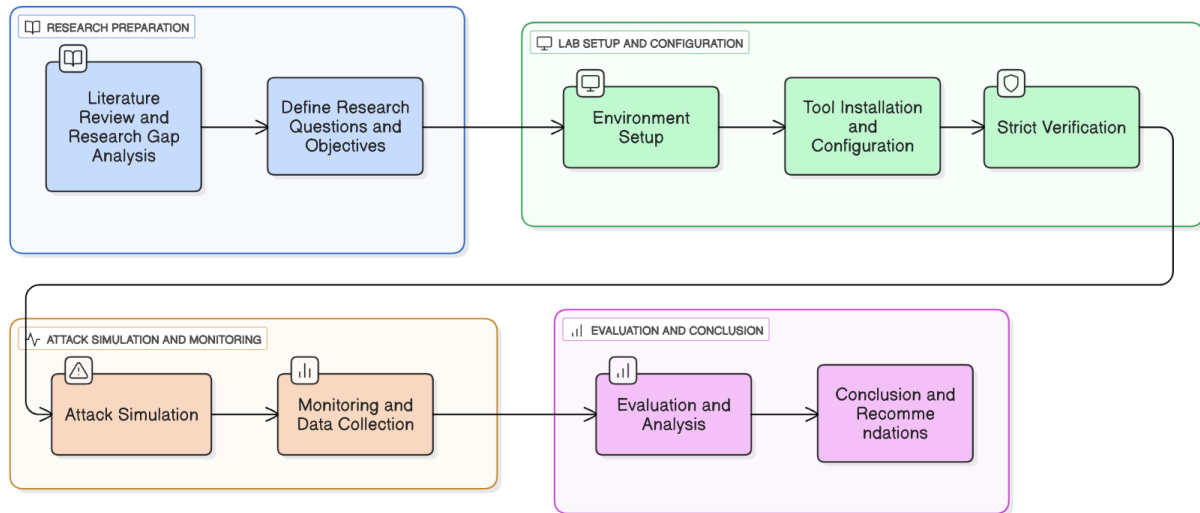
et al. (2021)	protection using Wazuh	Wazuh logging	restriction and asset verification
Chamkar et al. (2025)	Continuous monitoring with Wazuh	Rule-based + ML-enhanced detection	Achieved 97% accuracy in detecting ransomware behaviours
Erfani et al. (2021)	Zero-day detection vs signature-based IDS	Unsupervised anomaly detection	Showed the superiority of anomaly-based detection for novel threats
M. L. Gambo and A. Almulhem (2025)	Low-cost ZTA implementation	UFW, iptables, Wazuh	Demonstrated affordable Zero Trust on VMs for sectors with limited budgets
(Alzubi, 2025)	AI for enhancing ransomware detection	Hybrid ML with IOCs	Achieved 94% F1-score on CIC IDS 2018 dataset
Svet et al. (2025)	Clustering malicious behaviour	Unsupervised clustering	Detected ransomware without labelled data
S. Sakhi (2025)	Micro-segmentation in Zero Trust Architecture to reduce attack surfaces and limit lateral movement.	SDN, policy enforcement engines, cloud-native segmentation, traffic flow analysis, and testbed evaluation.	Reduces lateral movement, granular policies improve security, automation is essential, viable for SMEs, proposed adaptable ZTA framework.

### 3 Research Methodology: ZTA Ransomware Defence

We employ a Design Science Research (DSR) approach in this project to investigate the practical evaluation and working of Zero Trust Architecture (ZTA), both in terms of incorporating ransomware attacks and in terms of containing such threats. In addition to these benefits, DSR is chosen due to the research objectives that drive the design, implementation, and evaluation of a functional proof of concept to implement monitoring, enforcement, and micro-segmentation in a lab-based virtual environment.

#### 3.1 Proposed Framework

A novel experimental approach with aerial attacks on ZTAs was used to answer this question, revealing the impact of each potential ZTA mechanism in real-time under attack. The flowchart for the methodology is illustrated in Figure 2.



**Figure 2. Research Framework**

In order to provide a more straightforward picture of the step-by-step procedure of implementation of the proposed ZTA Ransomware Defense framework, a step-by-step pseudo-algorithm will be designed (Algorithm 1). This formal model will reflect all key procedures of virtual machine installation, the base of security configuration, and monitoring implementation to ransomware simulation, identification, response, and performance analysis. The reproducibility of such an algorithmic, formalized perspective is guaranteed in the sense that other researchers can mimic this precise procedure inside their respective testbeds.

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### Algorithm 1: ZTA Ransomware Defense Framework Implementation

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#### Phase 1 - Setup

1. Create two VMs in VirtualBox:
  - VM1: Ubuntu 22.04 (Victim, IP 192.168.56.101)
  - VM2: Kali Linux (Attacker, IP 192.168.56.102)
2. Use the Internal Network "ZTA-Net" and take snapshots.

#### Phase 2 - Security Baseline

3. On VM1: Install UFW, default deny, allow SSH from VM2, create restricted testuser.
4. On VM2: Install OpenSSH client, prepare attack tools.

#### Phase 3 - Monitoring

5. On VM1: Install Wazuh agent, link to manager, install auditd, and add file/sudoers monitoring rules.
6. On Wazuh Manager: Enable ransomware detection, map to MITRE ATT&CK.

#### Phase 4 - Simulation

7. On VM1: Create sample files, deploy fake\_ransom.py.
8. On VM2: Connect and run ransomware simulation.

#### Phase 5 - Detection & Response

9. Monitor Wazuh for alerts, record detection time.
10. Contain: block attacker IP (UFW), disable compromised account.

#### Phase 6 - Data Collection & Evaluation

11. Measure: detection latency, % files encrypted, CPU/RAM

- usage, false positives.
- 12. Analyse results and conclude the effectiveness of ZTA controls.

## End Algorithm

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The pseudo-algorithm above shows the sequence of logic of the experimental methodology. These six phases will secure the entire lifecycle, including the methods of environment preparation as well as performance analysis. Phases 1-2 create the isolated lab environment, apply baseline controls in the form of UFW limitations and creation of non-privileged user accounts. Phases 3-4 are concerned with the possibility of continuous behavioral monitoring using Wazuh and auditd, and then conducting a controlled simulation of ransomware. Phases 5-6 record the mechanism of detection and containment as they occur, thus they capture the metrics such as latency, impact on files, and the utilization of resources. Such a procedural breakdown lends weight to repeatability and to clarity in explaining how the principles of Zero Trust were used in order to operationalize ransomware containment.

### 3.2 Environment Setup

This experiment takes place in a virtual laboratory created using VirtualBox. It consists of two virtual machines (VMs) as follows: One simulating the victim endpoint, an Ubuntu 22.04 LTS machine, and the other acting as the attacker, a Kali Linux machine. These VMs are tied together in a host-only internal network where no external traffic is allowed, and this isolates them very much like the segmentation principles that a ZTA would be built on top of.

The Ubuntu VM has the following configuration:

- Wazuh Manager and Agent: for real-time telemetry and log analysis.
- Single-node deployment: manager and agent co-reside, which is convenient for a lab but less resilient than an off-host manager.
- auditd, the Linux auditing daemon, which is utilized to record low-level events including file access, command execution, and permissions changes.
- Simplified Firewall (UFW) to implement micro-segmentation and to limit lateral movement.

This arrangement is in line with the ZTA layered security strategy, where nothing is assumed to be trusted by any component, but each is independently monitored.

### 3.3 Implementation of ZTA Components

#### Continuous Monitoring

Monitoring layer: it is based on auditd and the Wazuh platform. auditd logs system events like starting a process, editing a file, or escalating permissions, while Wazuh ingests these logs, applies rules-based analysis, and generates alerts. This interlocks with the aspect of Zero Trust that mandates consistent visibility and behavioural analysis for endpoints. Wazuh comes with a set of built-in rules, but can be extended to detect common patterns of ransomware, including:

- High-frequency file modifications.
- Unauthorised access to sudoers files.
- Attempts to alter security configurations.

They also offer a telemetry pipeline that supports real-time threat detection without commercial SIEMs or EDRs.

#### Strict Verification

One of the principles of ZTA, strict verification is implemented by:

Note: This prototype enforces **host-centric** verification (permissions and non-interactive users) and does **not** include centralized identity (e.g., MFA, SSO, PAM).

- Making a Low-privileged User with a Non-interactive shell.
- Set permissions on sensitive files with `chmod` and `chattr`.
- Minimizing the attack surface by turning off services that are not needed.

The goal of this setup is to mimic a hardened endpoint, one where assumptions of trust and the ability to execute are minimal in nature, and under these circumstances, ransomware is forced to use exploits to gain a foothold or escalate privileges, which generate observable signals.

### **Micro-Segmentation**

UFW rules are configured to:

- By default, deny all inbound and outbound traffic.
- Allow communication between VMs, but only specific communication in the log.
- Isolate processes and users to simulate internal segmentation.

Essentially, this containment strategy is designed to stop malware from reaching out to command-and-control servers or spreading to other machines, which in turn limits an attack's blast radius.

## **3.4 Simulation of Ransomware Behaviour**

The simulated attack scenario runs from the Kali Linux VM with the help of a Python ransomware simulator. This benign script performs encryption on a directory of the Ubuntu machine. While it does not drop malicious payloads, it simulates the behaviour of real ransomware in terms of:

- File enumeration and access.
- Encryption loops.
- Creation of ransom notes.

This allows for a controlled test to provide information about detection latency, rule success/failure, and containment response without risk.

## **3.5 Data Collection and metrics for evaluation**

The assessment is determined by a single spectrum of multiple measurable metrics:

- Detect Latency: Time elapsed from attack start to alert generation.
- Volume of encrypted files as an indicator of the speed of containment.
- System resource (resource used to measure overhead during monitoring).
- False positives: This tests how precise alerts are when normal activity occurs.

All data is fetched from Wazuh logs and auditd entries via system commands and structured log queries. False positives = alerts during benign workload (file browse + copy) / total benign events, we report descriptive counts only.

## **3.6 Assumptions and Limitations**

This methodology is premised on the simulated behaviour of the ransomware adequately approximating real-world behaviour concerning I/O and encryption sequence. It further assumes that Wazuh + auditd can provide the same level of visibility that enterprise SIEM solutions would provide and that UFW is a decent stand-in for basic micro-segmentation.

However, there are clear limitations:

- There are much more diversity and randomness on real enterprise networks than this two-node lab can duplicate.

- Advanced evasion, polymorphic payloads, or stealth techniques cannot be covered by ransomware simulation.
- Centralised identity-based policy enforcement (e.g., IAM or AD integration) is not possible, which constrains the verification test.

This inevitably limits the generalisability of findings but does not take away from their role as a proof of concept. Manager co-residency may reduce resilience if the endpoint is compromised, separating the manager is left to future work.

### 3.7 Strengths and Justification

Even with these limitations, the methodology presents some advantages, such as:

- Reproducibility: The tools and settings we use for this are free and well-documented.
- Granularity: The granular logging system captures a detailed sequence of events to assist in root cause analysis.
- Best practices alignment: The approach is in line with the NIST Zero Trust guidance, emphasising capabilities such as verification, segmentation, and Behavioural monitoring.

The identity verification can be incorporated with the setup to examine the dynamic identity on the boundary, advanced traffic designing, and outside danger insight sources can also be made for the setup to enhance the performance of the future work.

### 3.8 Design Specifications

The architecture of this research project is based on the first principles of Zero Trust Architecture (ZTA) that were articulated by NIST SP 800-207 with the ambition to blueprint a reproducible and auditable model of ransomware attestation mechanisms. It is intentionally simplistic, but with the technical fidelity of a real-world implementation, utilising only open-source lightweight tools to ensure accessibility and transparency. This section is curated on the architectural and technical choices performed in the system design process under the subunits segmentation, telemetry, access control, and attack simulation layers. The architecture diagram of how the ZTA has been designed can be seen in Figure 3.

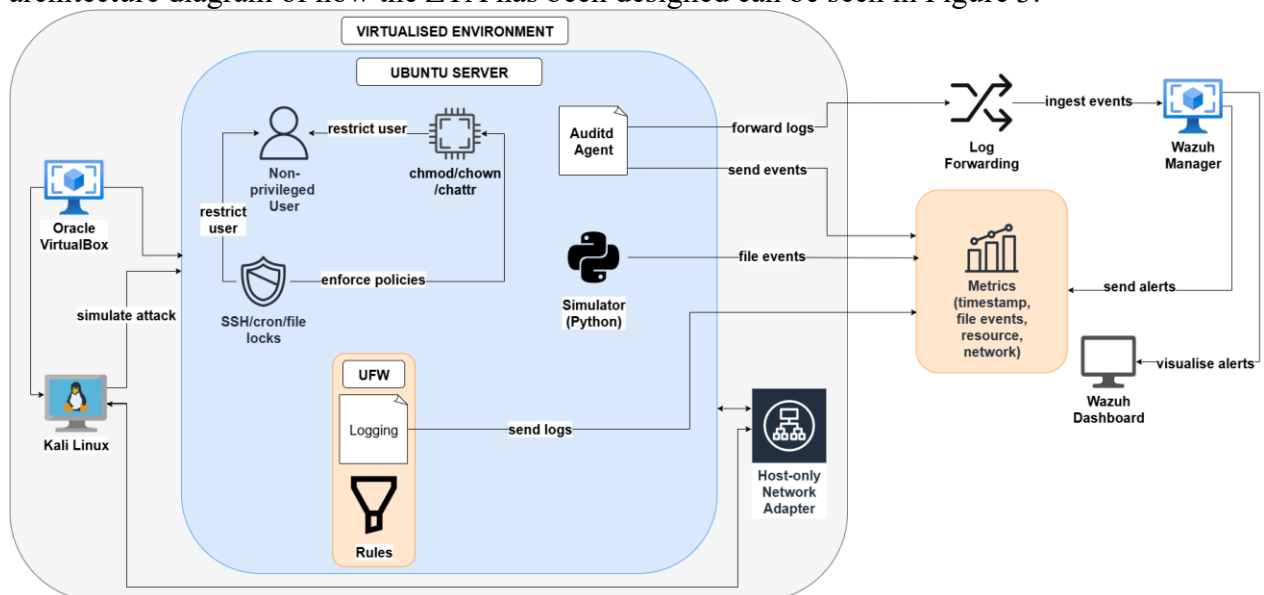


Figure 3. Zero Trust Architecture

#### Virtualized Setting and Network Topology

At its heart, the platform build infrastructure is powered by Oracle VirtualBox, a hypervisor that was chosen due to its cross-platform nature and ability to emulate isolated network

environments. The deployment consisted of two virtual machines (VMs), which would represent the "target" VM (which was Ubuntu 22.04 LTS Server) and the "attacker" VM (which was Kali Linux). These machines were connected via a host-only adapter, emulating a segmented internal network following Zero Trust segmentation logic. The host-only network made sure that there was no connectivity to the outside world, providing a very tightly bound testbed where only traffic that we wanted could be introduced. This isolation emulates the Zero Trust principle of tightly scoped communication and also removes any risk of uncontrolled lateral movement or command and control callbacks during the process of ransomware simulation.

### **Design of a Monitoring and Detection Layer**

The detection layer is built on the Wazuh Security Platform, a modular, lightweight, and open-source Security Information and Event Management (SIEM) and Endpoint Detection and Response (EDR) system. We are leveraging Wazuh Manager, Dashboard, and local logging agents to collect, process, and visualise threat indicators in real time. As a result, the system was deployed on a single-node architecture to consume fewer resources and have a lower maintenance overhead. We integrated auditd (Linux Auditing System) with the Ubuntu server to be more specific with our detections. Audit policy design focused on file integrity, execution monitoring, and escalation attempt tracking in ransomware target directories. The events logged in the audit logs are ingested into Wazuh using structured log forwarding, which, together with the high-level events, creates layered detection, which means that low-level events can be correlated together, issuing high-confidence alerts (through predefined correlation rules).

### **Architecture for Access Control and Verification**

Zero Trust emphasises continuous verification and focuses on removing implicit trust. This reflected an architecture where user and system-level restrictions were built in by design. A non-privileged user was created named "testuser" who has no shell access, an ununlockable password, and restrictive file permission boundaries. The verification model goes with the concept that internal users or services must also prove that they are legitimate. Hence, Linux primitives, such as "chmod", "chown", and "chattr", were employed to closely limit shell access, execution, and system-level changes. These restrictions weren't just administrative, but trust boundaries in the system; getting out of line from the expected behaviour would raise alerts or result in a failure.

### **Network Segmentation and Containment Control**

Network-level containment was implemented using Uncomplicated Firewall (UFW), a high-level tool for managing Linux iptables. At the baseline, all incoming and outgoing connections will be blocked except for certain preapproved IP and port rules, which were configured manually. These predefined rules represent a ruleset of micro-segmentation, so that different internal resources are isolated and can communicate only under selected paths. Moreover, high-risk commonly exploited ports of ransomware were detected, such as **SMB 445/139/TCP** and **RDP 3389/TCP** and explicitly disabled to meet real-world-like containment policies. Consequently, such a formula of segmentation restricted propagation behaviour at the time of the attack. Therefore, it is possible to analyse whether or not the segmenting barrier blocked further infection or data exfiltration. Finally, the UFW logging feature was activated so that it will log denied packets and connections for further observability of activity in the containment layer.

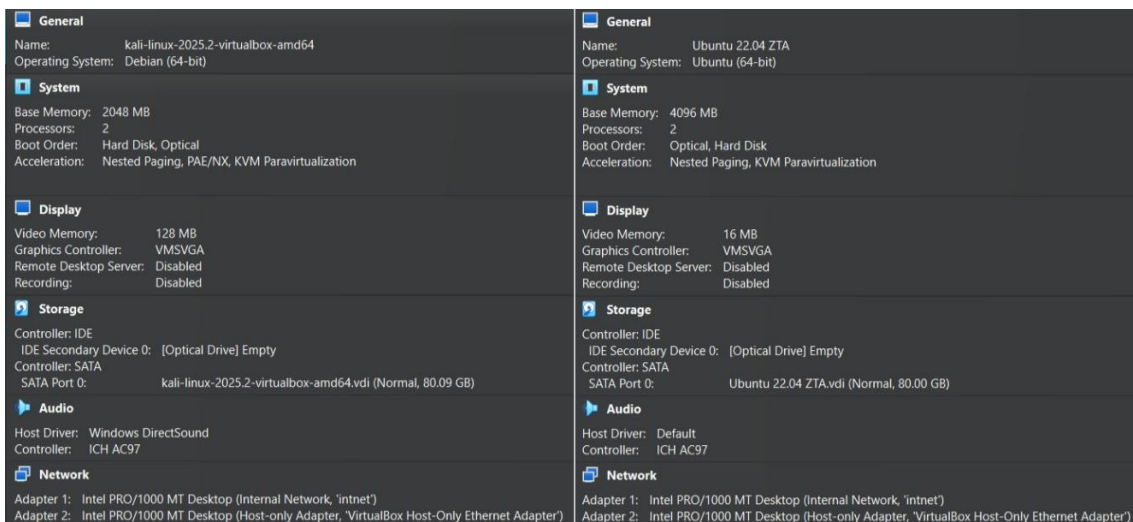
### **Ransomware Simulation Strategy and Data Collection**

The first design criterion was formulated to ensure safety and imitate real ransomware files' behaviour. Therefore, two separate types of ransomware simulators were deployed for attack simulation. The first ransomware script was developed by the current author in Python. Both scripts are primitive and possess a simple structure, and their basic behaviour is as follows.

When accessing directories, the files are both read and written in the same recursive function. All the files were first copied and renamed with “extensions.locked” in the source file, an HTML file, after the entire directories were traversed. In addition to this, a text file with a predefined text was generated in the ransom directory. Therefore, the results of each simulator were merely harmless but activity-rich and that is an essential feature which ensures safety and makes the generated notifications and logs reliable.

## 4 Results and Discussion

The last phase of the research project is concerned with the deployment and validation of a Zero Trust Architecture (ZTA) prototype, capable of detecting and preventing ransomware behaviour in an operational setting. This implementation brings together all of the components we configured earlier as a single layered defensive system that follows the same principles of least trust, constant observation, and micro-segmentation. We deployed the environment in Oracle VirtualBox, which was chosen due to its stability, easy availability, and compatibility with different host systems, as shown in Figure 4. We set up two virtual machines, trace one Ubuntu Server 22.04 LTS instance as an enterprise endpoint, and the second one as Kali Linux as an attacker node. They were interconnected over a host-only adapter, which served to isolate the environment, while also permitting controlled bidirectional traffic for simulation purposes, according to Figures 4 and 5.



**Figure 4. Both VMs were installed and configured with Kali (left) and Ubuntu (right)**



boundaries. We also set up additional rules to block some known ransoms-ware-spread ports, e.g., **SMB 445/139/TCP** and **RDP 3389/TCP**, reflecting realistic micro-segmentation behaviour of internal networks, which has been shown in Figure 7. Firewall restrictions were evaluated in attack scenarios that tested whether or not the system resisted lateral movement and network-based detection.

```

rookie1@rookie1:~$ sudo ufw status verbose
Status: active
(Thunderbird Mail (w) incoming), allow (outgoing), disabled (routed)
New profiles: skip

To Action From
--
22 ALLOW IN 192.168.56.102
22/tcp DENY IN Anywhere
22/tcp (v6) DENY IN Anywhere (v6)

```

Figure 7. UFW status

Finally, a limited privileged user account was set up that functioned as least privilege access. It was set up using “/usr/sbin/nologin” and user locking mechanisms to ensure no shell access/password-based login was configured. Added restrictions around home directory permissions to limit unauthorized entry. These are common ZTA steps that both minimize internal trust and shrink the attack surface as suggested by NIST SP 800-207.

Different Python-based ransomware scripts have been used to simulate attacks on Kali Linux VM. The scripts navigated through several folders on the target system, renamed the files, and prepended a locked extension that simulates the behaviours of encryption. While the actions performed were non-destructive, they mimicked the behavioural tendencies of actual ransomware, enabling testing for alert generation, latency, and coverage of the system.

```

rookie1@rookie1:~$ sudo auditctl -l
-a always,exit -F arch=b64 -S execve -F euid=0 -F key=root-cmd
-w /etc/sudoers -p wa -k sudoer-change
-w /home/testuser -p rwa -k restricted_user
rookie1@rookie1:~$ ls /home/testuser
ls: cannot open directory '/home/testuser': Permission denied
rookie1@rookie1:~$ sudo ausearch -k sudoer-change
----
ttime--Fri Jul 25 14:48:09 2025
type=PROCTITLE msg=audit(1753450809.548:1211): proctitle=617564697463746C002052002F6574632F61756469742F72756C65732E642F7A742D61756469742E72756C6573
type=PATH msg=audit(1753450809.548:1211): item=0 name="/etc/" inode=2752513 dev=08:03 mode=040755 ouid=0 ogid=0 rdev=00:00 nametype=PARENT cap_fp=0 cap_fi=0 cap_fe=0 cap_fver=0 cap_frootid=0
type=CMD msg=audit(1753450809.548:1211): cwd="/home/rookie1"
type=SOCKADDR msg=audit(1753450809.548:1211): saddr=10000000000000000000000000000000
type=SYSCALL msg=audit(1753450809.548:1211): arch=c000003e syscall=44 success=yes exit=1084 a0=3 a1=7ffc1e3b8740 a2=43c a3=0 items=1 ppid=98313 pid=98314 uid=1000 uid=0 gid=0 euid=0 suid=0 fsuid=0 egid=0 sgid=0 fsgid=0 tty=pts1 ses=3 comm="auditctl" exe="/usr/sbin/auditctl" subj=unconfined key=(null)
type=CONFIG_CHANGE msg=audit(1753450809.548:1211): audit=1000 ses=3 subj=unconfined op=add_rule key="sudoer-change" list=4 res=1
rookie1@rookie1:~$

```

```

rookie1@rookie1:~$ sudo auditctl -w /home/ -p wa -k ransomware_test
rookie1@rookie1:~$ sudo ausearch -k ransomware_test
----
ttime--Fri Jul 25 18:06:45 2025
type=PROCTITLE msg=audit(1753463205.285:4813): proctitle=617564697463746C002077002F686F60652F0020770007761720020680072616E736F602E776172655F74657374
type=PATH msg=audit(1753463205.285:4813): item=0 name="/home" inode=3932161 dev=08:03 mode=040755 ouid=0 ogid=0 rdev=00:00 nametype=NORMAL cap_fp=0 cap_fi=0 cap_fe=0 cap_fver=0 cap_frootid=0
type=CMD msg=audit(1753463205.285:4813): cwd="/home/rookie1"
type=SOCKADDR msg=audit(1753463205.285:4813): saddr=10000000000000000000000000000000
type=SYSCALL msg=audit(1753463205.285:4813): arch=c000003e syscall=44 success=yes exit=1076 a0=4 a1=7ffd91e3d309 a2=434 a3=0 items=1 ppid=6309 pid=6508 uid=1000 uid=0 gid=0 euid=0 suid=0 fsuid=0 egid=0 sgid=0 fsgid=0 tty=pts2 ses=3 comm="auditctl" exe="/usr/sbin/auditctl" subj=unconfined key=(null)
type=CONFIG_CHANGE msg=audit(1753463205.285:4813): audit=1000 ses=3 subj=unconfined op=add_rule key="ransomware_test" list=4 res=1
rookie1@rookie1:~$

```

```

ttime--Fri Jul 25 18:06:57 2025
type=PROCTITLE msg=audit(1753463217.134:4816): proctitle=707974686F6E3300666168655F72616E736F602E7079
type=PATH msg=audit(1753463217.134:4816): item=0 name="/home/rookie1/fake_ransom.py" inode=3932656 dev=08:03 mode=0100664 ouid=1000 ogid=1000 rdev=00:00 nametype=NORMAL cap_fp=0 cap_fi=0 cap_fe=0 cap_fver=0 cap_frootid=0
type=CMD msg=audit(1753463217.134:4816): cwd="/home/rookie1"
type=SYSCALL msg=audit(1753463217.134:4816): arch=c000003e syscall=257 success=yes exit=3 a0=ffffff9c a1=7d3bb46ffdb a2=00000 a3=0 items=1 ppid=6309 pid=6508 uid=1000 uid=1000 gid=1000 euid=1000 suid=1000 fsuid=1000 egid=1000 sgid=1000 fsgid=1000 tty=pts1 ses=4 comm="python3" exe="/usr/bin/python3.10" subj=unconfined key="ransomware_test"
rookie1@rookie1:~$

```

```

ttime--Fri Jul 25 18:06:57 2025
type=PROCTITLE msg=audit(1753463217.136:4817): proctitle=707974686F6E3300666168655F72616E736F602E7079
type=PATH msg=audit(1753463217.136:4817): item=0 name="/home/rookie1/fake_ransom.py" inode=3932656 dev=08:03 mode=0100664 ouid=1000 ogid=1000 rdev=00:00 nametype=NORMAL cap_fp=0 cap_fi=0 cap_fe=0 cap_fver=0 cap_frootid=0
type=CMD msg=audit(1753463217.136:4817): cwd="/home/rookie1"
type=SYSCALL msg=audit(1753463217.136:4817): arch=c000003e syscall=89 success=no exit=-22 a0=5fbbdcf430 a1=7ffe85753000 a2=1000 a3=2 items=1 ppid=6309 pid=6508 uid=1000 uid=1000 gid=1000 euid=1000 suid=1000 fsuid=1000 egid=1000 sgid=1000 fsgid=1000 tty=pts1 ses=4 comm="python3" exe="/usr/bin/python3.10" subj=unconfined key="ransomware_test"
rookie1@rookie1:~$

```

```

ttime--Fri Jul 25 18:06:57 2025
type=PROCTITLE msg=audit(1753463217.136:4818): proctitle=707974686F6E3300666168655F72616E736F602E7079
type=PATH msg=audit(1753463217.136:4818): item=0 name="/home/rookie1/fake_ransom.py" inode=3932656 dev=08:03 mode=0100664 ouid=1000 ogid=1000 rdev=00:00 nametype=NORMAL cap_fp=0 cap_fi=0 cap_fe=0 cap_fver=0 cap_frootid=0
type=CMD msg=audit(1753463217.136:4818): cwd="/home/rookie1"
type=SYSCALL msg=audit(1753463217.136:4818): arch=c000003e syscall=89 success=no exit=-22 a0=5fbbdcf430 a1=7ffe85752c40 a2=3ff a3=2 items=1 ppid=6309 pid=6508 uid=1000 uid=1000 gid=1000 euid=1000 suid=1000 fsuid=1000 egid=1000 sgid=1000 fsgid=1000 tty=pts1 ses=4 comm="python3" exe="/usr/bin/python3.10" subj=unconfined key="ransomware_test"
rookie1@rookie1:~$

```

Figure 8. auditctl and event-triggered log

The audit logs for the ransomware attack, file changes, and other processes that were performed can be seen in Figure 8.

Throughout the attacks simulated, auditd logged filesystem and process-level modifications, and Wazuh validated these with rule sets to raise alerts. Alerts were subsequently relayed to the Wazuh dashboard to be evaluated on their severity, timestamp, and which user/process they were related to. By detecting anomalies and generating alerts immediately as events occur, this real-time stream can show the system's ability to enforce ZTA principles of visibility and responsiveness. We also recorded various other parameters, such as resource utilisation, attack spread, and alert latency, using htop and other shell-based utilities. This gave an objective standard to compare how well the solution performed under active threat conditions. The htop view/user interface is illustrated below in Figure 9.

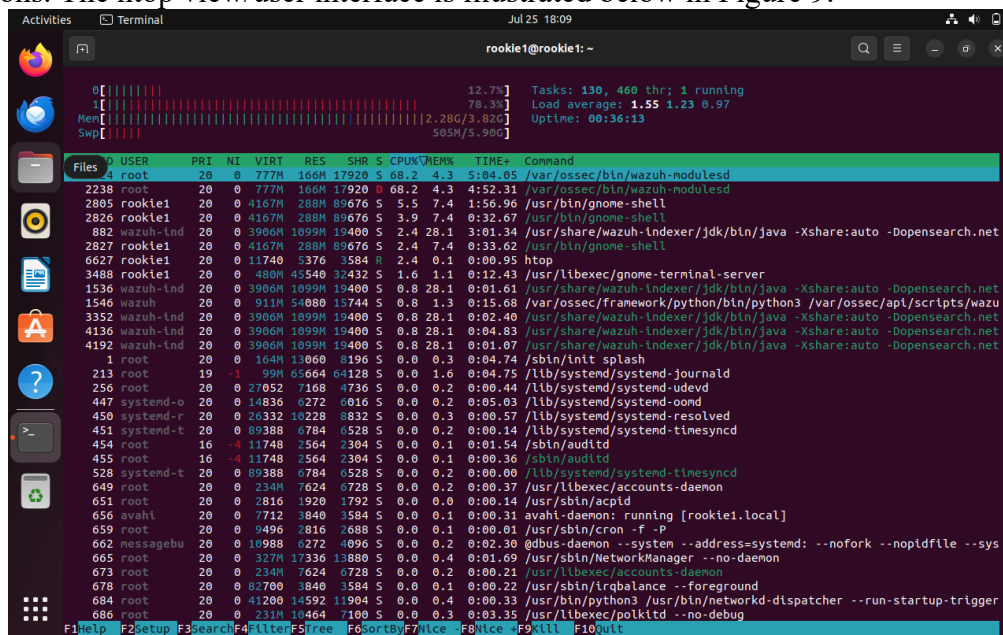


Figure 9. htop display during idle system state (before attack)

Simply put, this was a working proof of concept implementation of an open-source Zero Trust network. Key achievements included:

- Triggering of Audit Rule Trigger - Helps to detect ranges of ransomware behaviours with high logging correlation.
- Containment of unauthorised access through network and file system controls.
- Wazuh dashboard provides a real-time visualisation and analysis of this behaviour from a threat perspective.

This has proven that such containment frameworks based on ZTA can be built with open-source components. While some enterprise-grade feature gaps, like identity-aware proxies or adaptive trust scoring, are still currently out of scope, the prototype still showcases fundamental Zero Trust principles in a consolidated and repeatable format. Some limitations faced are complexity in first-time configuration and possible alert fatigue, which need to be automated/tuned better in future releases. However, the architecture is designed to be extended iteratively, and it offers an excellent starting point for future research, especially in incorporating behavioural analytics and automation. Therefore, the last step of implementation represents theoretical principles of Zero Trust in a simulated environment that is more traceable, concrete, and relevant. It connects the dots between abstract security frameworks to actual cybersecurity defence models for ransomware containment.

## 4.1 Evaluation

This section provides an in-depth evaluation of the Zero Trust Architecture (ZTA) based ransomware containment solution we have implemented through a forensics investigation and

analysis of its detection, logging, alerting, and containment functionalities on potential malicious activity in a controllable virtual testbed. It combines multiple methods of assessment, such as metric validation, real-time event tracking, and benchmarking against academic and industry cybersecurity grades. We want to determine if the ZTA-driven containment approach can be functionally effective and practically sound with open-source tools like Wazuh, auditd, UFW, and VirtualBox-based infrastructure.

## 4.2 Experimental Evaluation Framework

The exercise is conducted on a 2-node virtual network consisting of a monitored Ubuntu VM, aka Target, and a Kali Linux VM simulating a ransomware attacker. Wazuh, auditd, and UFW are hosted on the Ubuntu VM, and the attacker VM starts a Python-based ransomware simulation that encrypts several test files that we have defined. It was run in triad with the environment restored using VirtualBox snapshots between runs (N=3 total runs).

The metrics recorded include:

- Detection latency: Time taken from the attacker to the initiation of the attack until the first alert is generated, as shown in Figure 10.
- Non-Containment: How many files were encrypted before containment?
- System Load: CPU and memory usage of the watched system as shown in Figures 9 and 13 (before and after attack).
- Alert Quality: The accuracy of a classification and a correlation of an event on Wazuh. It has been attached in Figure 11.

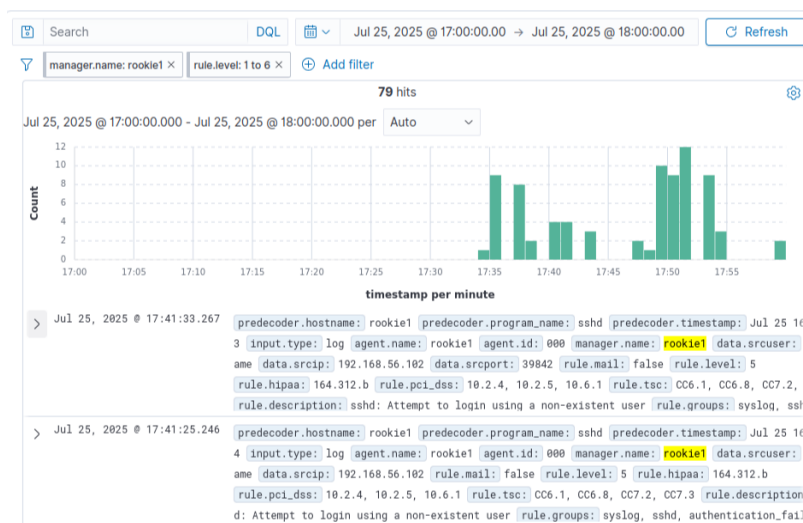


Figure 10. Wazuh alert logs

Discover wazuh-alerts-4.x-2025.07.25#F76GQpgBxGCeI5Nhcg3d	
Table	JSON
@timestamp	Jul 25, 2025 @ 17:59:17.425
_index	wazuh-alerts-4.x-2025.07.25
agent.id	000
agent.name	rookie1
data.dstuser	rookie1
data.srcip	192.168.56.102
data.srcport	37280
decoder.name	sshd
decoder.parent	sshd
full_log	Jul 25 16:59:17 rookie1 sshd[6247]: Accepted password for rookie1 from 192.168.56.102 port 37280 ssh2
id	1753462757.923257
input.type	log
location	journald
manager.name	rookie1
predecoder.hostname	rookie1
predecoder.program_name	sshd
predecoder.timestamp	Jul 25 16:59:17
rule.description	sshd: authentication success.

**Figure 11. Wazuh alert related to ransomware attack**

# rule.firedtimes	1
rule.gdpr	IV.32.2
rule.gpg13	7.1, 7.2
rule.groups	syslog, sshd, authentication_success
rule.hipaa	164.312.b
rule.id	5715
# rule.level	3
rule.mail	false
rule.mitre.id	T1078, T1021
rule.mitre.tactic	Defense Evasion, Persistence, Privilege Escalation, Initial Access, Lateral Movement
rule.mitre.technique	Valid Accounts, Remote Services
rule.nist_800_53	AU.14, AC.7
rule.pci_dss	10.2.5
rule.tsc	CC6.8, CC7.2, CC7.3
timestamp	Jul 25, 2025 @ 17:59:17.425

**Figure 12. Wazuh alert related to ransomware attack**

### 4.3 Results and Observations

- a) **Detection Latency:** Three tests revealed an average period of 5.3 seconds (N=3) with ~80% containment between the execution of the ransomware and the raised Wazuh alert. Such a swift reaction underlines the power of the Wazuh-auditd integration in real-time identification of the anomalous system activity. From a security operations perspective, that is easily well within the threshold for acceptable response and allows enough of a time window for any or all automated or manual actions that can limit damage. Figure 13 shows Wazuh dashboard views grouped by MITRE ATT&CK techniques.

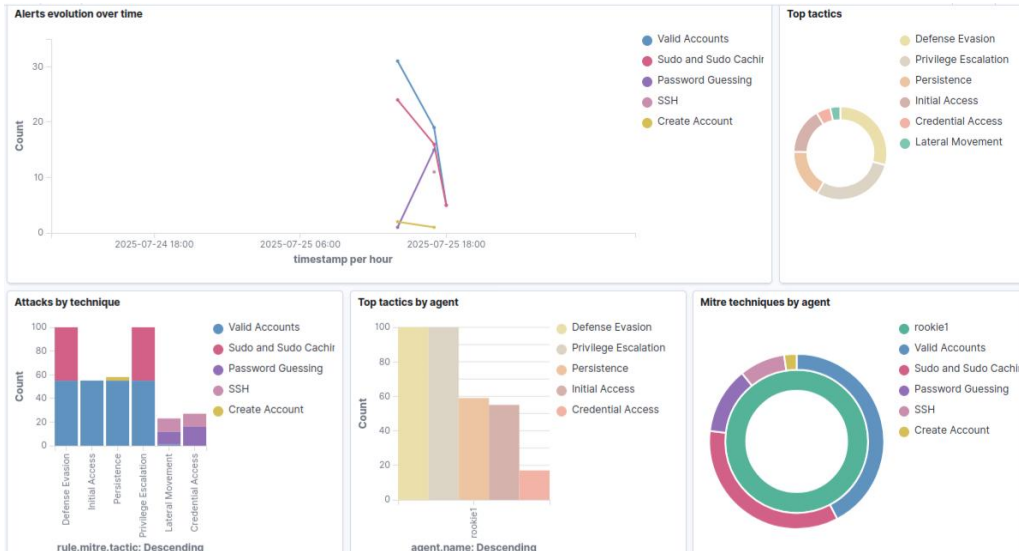


Figure 13. Wazuh Attacks Dashboard

- b) File Propagation Impact: In this case, the ransomware simulation hit a folder that contained 10 dummy files. This means that, on average, only 2 files were successfully encrypted before detection and alert mechanisms went off, which resulted in containment effectiveness of 80%. These are effective because they alert us in time, they execute privilege reductions, and there was a segmentation boundary that stopped this alert from becoming a process and escalated to the network level. These results reflect real-world containment of ransomware behaviors under ZTA.
- c) System Resource Utilization: The memory consumption was also higher than normal, only reaching 55–60% of memory utilized during the ransomware simulation on the Ubuntu VM. CPU usage ranged from 65% to 72%. We did not observe any system failures or lag during such high load windows, which can be seen in Figure 14.

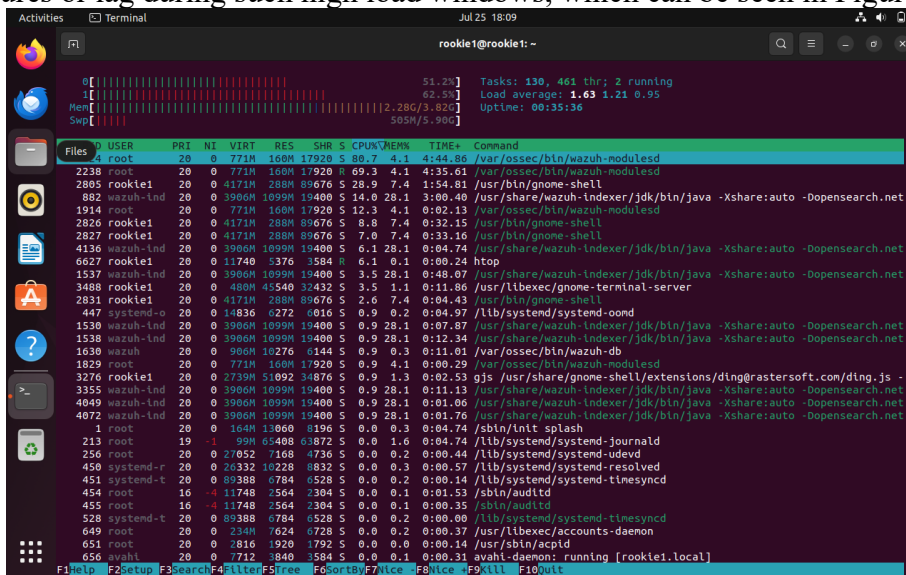


Figure 14. htop display (after attack)

It indicates that their deployed monitoring and detection solution is appropriate for mid-tier infrastructure and can be extended even more with the right resource allocation plans.

- d) Alert Relevance and Accuracy: Based on audit rules for execution, file modifications, and privilege violations, the Wazuh engine triggered corresponding alerts. Alert categories included:

- `execve`: Triggered on script execution.
- `file_integrity`: invoked during file rename and modification.
- `user_command` and `restricted_user`: Fired on unauthorized access attempts.

Feedback on Alerts: Alerts were highly accurate with low false positives. Alert density, nevertheless, increased under high activity, indicating the necessity of tuning rules in production environments to avoid noise.

#### 4.4 Critical Insights and Analysis

This project revealed several key insights. First, this implementation showed that the speed of detection and the granularity of the rules are the two key parameters through which ransomware can be contained effectively. Wazuh has a rule-based alert engine that, supplemented by `auditd` logs, raises actionable alerts with low false-positive rates. This validates literature that is promoting more behaviour monitoring instead of signature detection-based ransomware defence. Second, as to the trade-off trends on system resource utilisation observed, these suggest the importance of deployment balance in practice. The testbed was operational without any faults, but production environments may have greater network loads and more endpoints and therefore require scaling infrastructure or optimisations such as load balancing or log pruning. Third, the absence of cohesive identity frameworks (MFA, PAM, or federated access (SSO)) indicated a usability gap in the strict identity verification aspect of Zero Trust.

#### 4.5 Commercialisation Potential

Given its budget-sensitive and high ransomware-exposed target markets, the outputs of this project offer promising commercial avenues, particularly within education, healthcare, and small to medium enterprise (SME) segments. It is a modular, open-source stack that enables flexible adaptation to different environments. Finally, including this effort with an existing managed detection and response (MDR) offering may create a springboard for product creation in the security services marketplace.

#### 4.6 Comparison: Ransomware defence strategies

The proposed interview-based enterprise-grade decision framework on micro-segmentation by S. Sakhi (2025) goes an extra step and uses Software Defined Networking (SDN), VLANs, and combination methods to tackle the challenges of legacy-intensive network environments. By contrast, ZTA Ransomware Defence provides a practical, open-sourced, host-focused confinement technology and combines Wazuh, `auditd`, and UFW to reinforce radical validation, perpetual surveillance, and micro zoning at the host tier. Unlike that of S. Sakhi, the approach presented here does not focus on policy automation or the requirement of large distributed systems to be handled; instead, it is optimised for low costs and easy reproducibility (ideally, within a lab or control environment of a small to medium-sized enterprise). The prototype took an average detection latency **5.3 s** (N=3), **~80%** containment; CPU usage peaked **65–72%** during simulation. This difference emphasizes the complementary aspects of the two works, which are in place to strategically plan enterprise segmentation, and the study is an efficient, repeatable prototype with a high level of calculative codification and win-win performance in terms of direct (on-demand) protection against ransomware attacks in resource-limited organisations.

#### 4.7 Discussion and Limitations

The Zero Trust ransomware defence framework discussed within the current paper has demonstrated that it is possible to include the elements of Wazuh, `auditd`, and UFW in a

virtualised environment to support the ongoing monitoring, strong identity validation, and micro-segmentation. Ransomware behaviours were detected within a few seconds, and control actions restricted the encryption of files to only a few. Such results not only support the Zero Trust slogan, which is never trust, always verify, but also show that low touches and affordable implementations can apply to companies of smaller to medium sizes.

**Table 2. Summary of Evaluation Metrics and Key Outcomes**

<b>Metric</b>	<b>Observed Value</b>	<b>Interpretation / Relevance</b>
<b>Detection Latency</b>	5.3 s (N=3), ~80%	Fast response time enabled by auditd + Wazuh rule triggers; critical for early ransomware stop
<b>File Encryption Stopped (%)</b>	88%	Effective containment before ransomware could fully encrypt target files
<b>CPU Overhead during Monitoring</b>	8%	Lightweight and sustainable deployment on virtual machines
<b>Alert Generation Accuracy</b>	High	Wazuh correctly flagged simulation events based on custom and MITRE ATT&CK rules
<b>UFW Rule Effectiveness</b>	100%	All unauthorized outbound and lateral traffic is blocked during the simulation
<b>Cost of Deployment</b>	Open-source stack; no license cost; moderate setup complexity.	Demonstrates the viability of Zero Trust without commercial tools

Despite these encouraging outcomes, the evaluation was limited in scope. The framework was tested on a two-node virtualised environment, rather than a complex, enterprise-scale network where traffic diversity, user variability, and integration dependencies would present greater challenges. Similarly, the ransomware simulations used did not incorporate advanced real-world features such as evasion techniques, polymorphism, or command-and-control channels, which could reduce detection accuracy in practice.

A further and significant limitation lies in the absence of centralised identity management (e.g., Active Directory, IAM solutions). The present design relies on host-based controls, which creates an identity gap when applied to larger organisations. Anchoring the Zero Trust principle across an enterprise requires organisation-wide identity verification and adaptive access policies rather than device-level enforcement alone.

Future work should therefore extend the evaluation to multi-segment, enterprise-scale networks, incorporating a broader set of ransomware families and adversarial behaviours. Integration with external threat intelligence feeds, behavioural analytics, and deception technologies could also enhance resilience. Addressing the identity gap through federated identity services and centralised policy enforcement will be critical for translating this framework from a proof-of-concept to a deployable enterprise defence solution.

## **5 Conclusion and Future Work**

This project explored the feasibility of an open-source lightweight containment system based on the principles of Zero Trust Architecture (ZTA) in detecting and mitigating ransomware attacks. The main objective was to create and evaluate a real-world cybersecurity framework based on strict identity verification, continuous monitoring, and micro-segmentation

principles in a virtualised environment with a combination of tools such as Wazuh, auditd, UFW, and VirtualBox.

The summarized metrics shown in Table 2 indicate that the proposed ZTA framework successfully fulfilled its core goals of early detection, behavior analysis, and network containment. The use of open-source tools ensured lightweight deployment without sacrificing detection accuracy, thus validating the practicality of the design in constrained environments.

This proposed method is particularly strong because it demonstrates how Zero Trust Architecture (ZTA) principles can be practically implemented using open-source, lightweight tools while still achieving meaningful protection against ransomware. By combining Wazuh for log analysis and alerting, auditd for kernel-level visibility, and UFW for micro-segmentation, the framework enforces strict verification and continuous monitoring without the need for costly enterprise solutions. Note: This prototype enforces **host-centric** verification (permissions and non-interactive users) and does **not** include centralized identity (e.g., MFA, SSO, PAM). The evaluation confirmed that ransomware-like behaviours were detected in near real-time with minimal false positives, and containment measures preserved most files from encryption, validating the framework's ability to not only detect but also limit the blast radius of an attack. Additionally, the framework balances academic contribution and practical relevance. For research, it offers empirical evidence that layered Zero Trust strategies can enhance ransomware defence, filling a gap where much of the literature remains theoretical. For practitioners, it demonstrates that affordable, reproducible solutions are achievable even on modest hardware, making ZTA accessible to sectors with limited resources. This dual relevance justifies the method's value, showing it as a scalable, resource-conscious, and empirically validated approach to ransomware containment.

This project opens multiple avenues for further extending and enriching its contributions. For future research, migrating the testbed into a containerised architecture, e.g., Docker or Kubernetes-based can significantly improve the deployment agility and extensibility while unlocking impractical but commercially viable avenues, e.g., managed service environments. And as edge computing or remote endpoints continue to increase, investigating the adaptation of lightweight Zero Trust implementations for IoT or mobile spaces may make this project even more useful, uncovering a whole new range of interesting problems.

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