Leveraging Intel SGX and Hybrid Design for Secure National ID Systems

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Jan 2025

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This is to certify that the thesis proposal is prepared by Tesfalem Fekadu titled: "Leveraging Intel SGX and Hybrid Design for Secure National ID Systems". Submit in partial fulfillment of the requirement for the Degree of Master of Science in Cybersecurity (Network and System Security) complies with the regulations and guideline of the university and meets the acceptable standard concerning originality and quality.

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Abstract

Globally, 1.1 billion individuals, including 21 million refugees, lack proof of legal identity, disproportionately affecting children and women in rural areas of Asia and Africa. Without official identification, access to essential services such as education, healthcare, banking, and public distribution systems becomes nearly impossible. The increasing reliance on digital identity management systems demands robust security measures to safeguard sensitive personal data.

The Modular Open-Source Identity Platform (MOSIP) is a widely adopted solution due to its flexibility and scalability. However, protecting sensitive data during National ID enrollment, registration, and authentication processes remains a significant challenge. Specifically, decrypting biometric data before feature comparison in server environments exposes this data to critical vulnerabilities, increasing the risk of potential attacks. The reliance on software-based Software Development Kits (SDKs) for biometric matching exacerbates the issue, as these SDKs often operate alongside other software modules, expanding the attack surface. Software-based approaches are inherently risky due to the high likelihood of exploitable bugs, which attackers can use to compromise data integrity or gain unauthorized access. This study addresses these security challenges by integrating Trusted Execution Environments (TEEs) to enhance data protection during processing. A hybrid architecture is proposed, incorporating an SGX-based solution named **SGX-BioShield** to improve the security and hybrid architecture for performance enhancement. A prototype of the proposed security solution has been developed and tested, demonstrating that **SGX-BioShield** significantly reduces the risk of unauthorized access and data breaches by isolating sensitive operations within a hardware-protected environment. Intel SGX ensures that data remains secure even if the operating system or hypervisor is compromised. This research contributes to the field of identity management by presenting a novel approach to securing platforms like MOSIP. It provides practical insights into improving data security and overall system performance through the implementation of a hybrid architecture in digital identity systems.

- **Keywords:** Identity management systems, MOSIP, Intel SGX, SGX-Bioshield, data security, open-source software, secure enclaves, digital identity

Acknowledgments

My advisor, Dr. Sileshi Demisie (PhD), deserves special recognition because he oversaw my work, made the effort to read it, and offered insightful feedback at every stage, beginning with the choice of titles and continuing right up until this point. I would also like to express my gratitude and appreciation to my Sister selamawit Fekadu, my wife Miracle Lombardia, as well as my friend, Seada Mohamed Amanuel Majore, a for their encouragement and support, both in terms of their moral and material contributions.

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Abbreviations and acronyms

API	Application Programming Interface
GD	Gramine-Direct
GDPR	General Data Protection Regulation
GS	Gramine-SGX
HSM	Hardware Security Module
KMS	Key Management Service
MOSIP	Modular Open Source Identity Platform
OTP	One-Time Password
SAML	Security Assertion Markup Language
SGX	Software Guard Extensions
SGX-SDK	SGX Software Development Kit
TLS	Transport Layer Security
UI	User Interface
IDMS	Identity Management System

CHAPTER ONE

1 Introduction

1.1 Background information

Over 1.1 billion individuals worldwide are unable to verify their identity, which prevents them from accessing essential services such as healthcare, education, social protection, and financial resources [5]. Identity enables individuals to actively participate in global development, empowering them as global citizens. Achieving this often requires individuals to reliably verify their identity. This empowers them to engage in financial services, voting rights, business rights, land titles, social protection, school and various other benefits. With the rise of digital transformation, the importance of digital identities is increasing, allowing individuals to access essential services. Implementation of digital ID systems that provide people with proof of legal identity, which is commonly needed to access basic services, rights, and protections. [9] Digital ID is a critical piece of digital public infrastructure; it is one of the three pillars of what's known as digital public infrastructure (DPI), the others are digital payment systems and data exchange systems. [10 Without these widely accepted types of valid identification, people may face the risk of being left out. [11]. Due to which, the need for reliable and secure digital identity management systems (IDMS) is growing [6]. One such platform, the Modular Open-Source Identity Platform [2]. This Modular Open Source Identity Platform (MOSIP) provides the technical foundation for digital ID system, ensuring that it is scalable, customizable, and supports minimal data collection, with data encrypted at all times to safeguard privacy [7]. In general, the digital identity system operates over three main phases: enrolment, authentication and authorization the enrolment phase are the process of creating and linking a real person (with/without verified documents) to a digital identity in a database that has three properties [16]. The act of ensuring that identities are distinct for registration within a system is known as de-duplication. Credential Issuing refers to the process of granting individuals a new identification token (such as a card or unique number) for self-identification purposes. Accretionary IDs enable individuals without documentation to establish an initial identity based on minimal evidence or supporting documents. These IDs are initially

assigned a low level of confidence, but their reliability and trust level improve as more information is received.

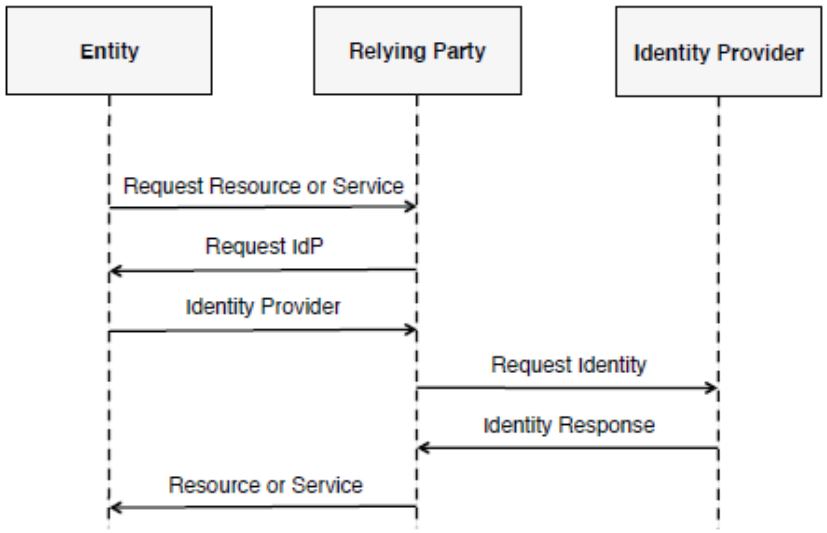

Figure 1. Entities in an IDM system (54)

1.2 Trusted Execution Environment (TEE)

Trusted Execution Environments (TEEs) have been widely used in many security-critical applications. The popularity of TEEs derives from its high security and trustworthiness supported by secure hardware Trusted Execution Environment (TEE) is a secure, isolated area within the CPU and memory, protected through encryption to prevent unauthorized access and tampering by external code [82]. Within the TEE, authorized code can process data directly, while anything outside can only access encrypted forms of that data, with security managed by an embedded platform processor [79]. The Trusted Computing Base (TCB), which consists of key hardware, firmware, and software elements such as TEEs, plays a vital role in system security, as a breach of any component within the TCB can jeopardize the entire system. By minimizing the TCB, the likelihood of attacks is diminished. Intel Software Guard Extensions (SGX) is a prominent example of a TEE that establishes an isolated environment on an untrusted operating system, thereby ensuring run-time protection for the execution of security-sensitive code and data. [82]. TEEs, such as Intel's Software Guard Extensions (SGX) and AMD SEV-SNP, use hardware root-of-trust mechanisms to generate cryptographic proofs for workload validation, with SGX

providing granular code-level control and SEV-SNP enabling entire virtual machines within the TEE, thus supporting flexible, secure environments specially cloud computing [80].

1.3 Intel Software Guard Extensions – SGX

Intel's Software Guard Extensions (SGX) is a set of hardware security extensions integrated into Intel processors. SGX provides integrity and confidentiality guarantees for security-sensitive computation, even in environments where privileged software, such as the operating system and hypervisor, may be compromised. SGX achieves this by creating a protected area in memory known as an "enclave," which isolates sensitive code and data from all other processes, including higher-privileged software and hardware peripherals. By encrypting the enclave's memory and restricting access to it, SGX ensures both data confidentiality and computation integrity, maintaining the security of sensitive computations. This is especially valuable in cloud or other untrusted environments where sensitive data must be processed securely [80].

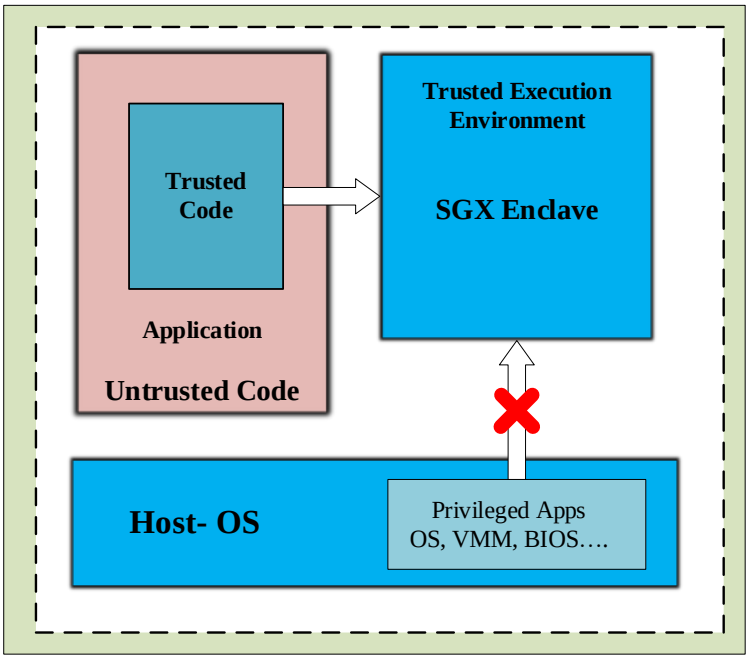

Figure 2. Intel SGX Architecture: Trusted Execution Environment and Isolation

SGX also includes a process known as "attestation," which cryptographically verifies that the enclave is executing trusted code. During attestation, the enclave generates a hash of its initial state, signed by a unique hardware attestation key. This proof allows remote parties, such as clients or data owners, to verify that they are interacting with a genuine and secure SGX enclave. By

enabling secure remote computation, SGX ensures that sensitive computations can be trusted, even when conducted on potentially untrusted infrastructure [80].

1.3.1 Key Security Elements of MOSIP Authentication System

The **Hardware Security Module (HSM)** is a robust physical device uniquely engineered for cryptographic processing and advanced authentication. It is responsible for encrypting, decrypting, generating, storing, and overseeing digital keys while also serving functions related to signing and authentication. Access to HSMs can be accomplished through PKCS11 and JCE interfaces [2].

Key Manager Key Manager: The Key Manager Service offers secure storage, provisioning, and administration of confidential data. It handles all cryptographic functions such as encryption/decryption and digital signature/verification, creating a centralized trust store for validating all partner trust paths [2]. The Key Manager oversees the entire lifecycle of encryption/decryption keys, which includes their generation, distribution, management, and deletion. The Key Manager interacts with key stores such as Hardware Security Module (HSM) and mosip_keymgr DB [2].

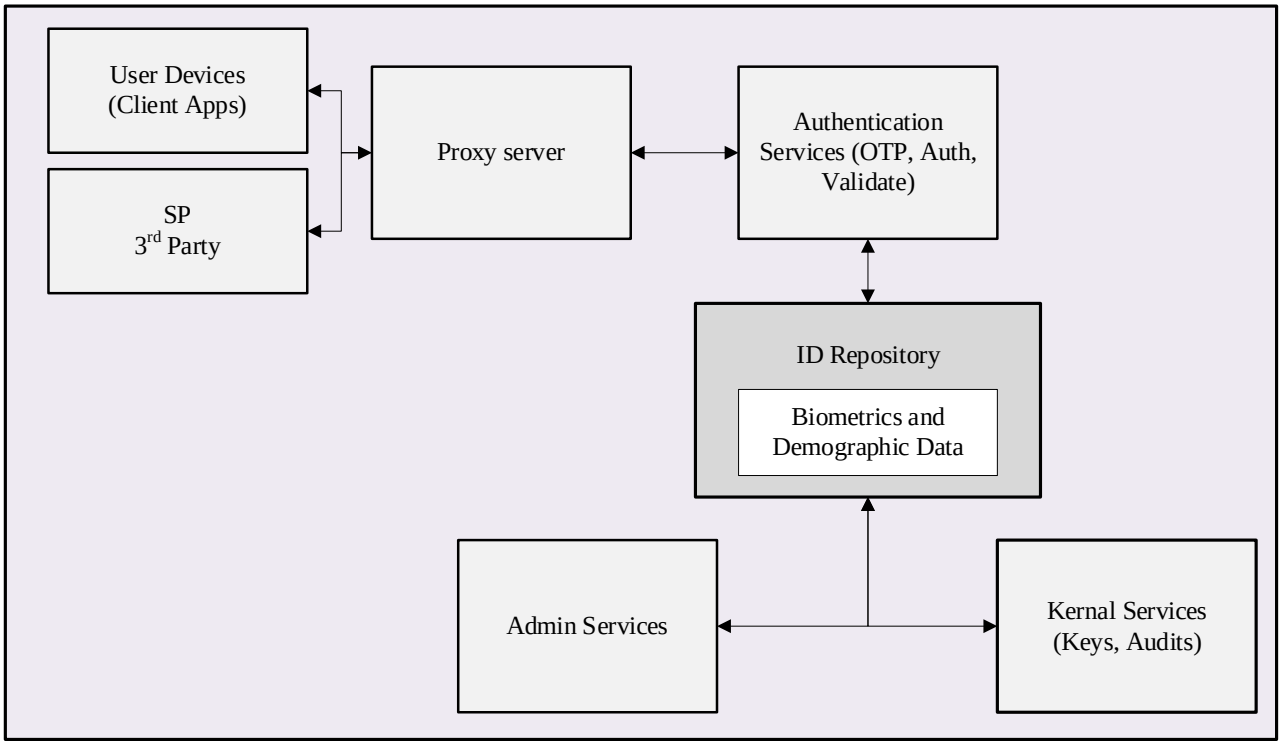

Figure 3. MOSIP Architecture for Secure Authentication and ID Repository Management

This architectural block diagram illustrates the basic framework of the MOSIP (Modular Open-Source Identity Platform) system. Below is a description of its components and flow:

User devices, such as client applications, serve as access points for end-users to connect to identity-related services, communicating with the system through a proxy server. Service Providers (SPs), which are third-party entities, integrate with MOSIP to utilize its authentication and identity verification functionalities. The proxy server plays a crucial role as an intermediary, managing and securing communication between user devices, SPs, and MOSIP's core services.

The system's authentication services encompass processes like OTP generation, user credential verification, and data validation, ensuring accurate identity authentication. At the core of the MOSIP framework is the ID Repository, a centralized database that securely stores biometric and demographic data. This repository includes a specialized component dedicated to sensitive information such as fingerprints, iris scans, and other demographic details.

Kernel services are integral to backend operations, handling tasks like cryptographic key management, system audits, and other security measures, ensuring the framework's reliability. Admin services provide interfaces for administrators to oversee the ID repository, configure system settings, and monitor operations.

The data flow within the system begins with user devices and SPs sending requests to the proxy server, which then forwards them to authentication services. These services interact with the ID Repository to verify user data, with kernel services ensuring security and cryptographic support. System administrators use admin services to manage and maintain the system effectively.

ID Authentication Functionality: Authentication refers to the method of confirming an identity claim by comparing it with the registered identity data. This data may include personal identification information (PII) such as demographic details, biometric data like fingerprints, iris scans, or facial recognition, as well as a one-time password (OTP) sent to the registered email or phone number. MOSIP offers APIs that allow individuals to carry out these authentication processes after they have registered with MOSIP. Authentication within MOSIP can be conducted by authorized partners through a secure network established by MOSIP Infrastructure Service Provider.

Authentication requests must come from trusted, white-listed partners in MOSIP, and biometric devices must be registered with the system. Data used for authentication includes demographic details (name, date of birth, gender, address) and biometrics (fingerprint, iris, face). For added security, a second authentication factor, such as OTP, static PIN, or challenge-response, is supported. All authentication requests are audited for security analysis, including fraud detection [2].

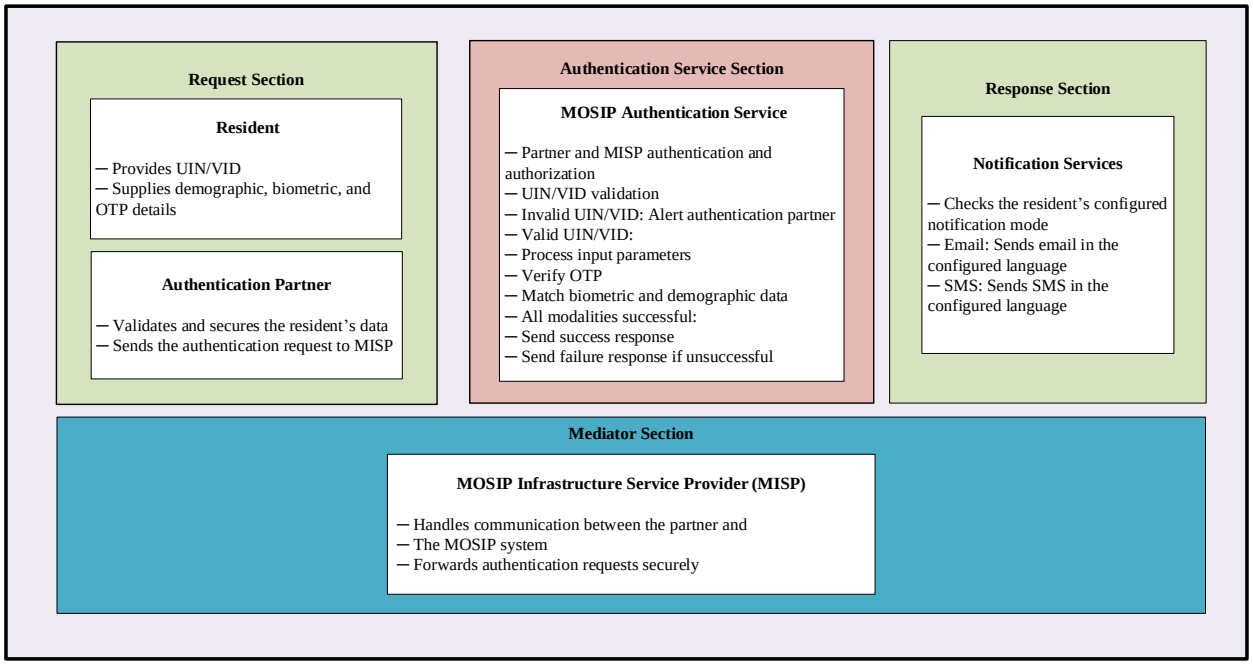

Figure 4. MOSIP Authentication Workflow Diagram of user request

The provided diagram illustrates the MOSIP (Modular Open-Source Identity Platform) Authentication workflow, dividing it into four key sections: **Request**, **Mediator**, **MOSIP Authentication Service**, and **Response**, each with distinct roles and responsibilities. The **Request** section involves the resident and the authentication partner. The resident initiates the process by providing their Unique Identification Number (UIN) or Virtual ID (VID) along with demographic, biometric, and One-Time Password (OTP) details. The authentication partner, on the other hand, validates the resident's data, ensures its security, and forwards the authentication request to the MOSIP Infrastructure Service Provider (MISP).

The **Mediator** section highlights the role of the MISP, which serves as a secure communication bridge between the authentication partner and the MOSIP system. The MISP securely forwards the authentication requests while maintaining data integrity and confidentiality, ensuring a secure

handoff to the core authentication service. The **MOSIP Authentication Service** then takes over, performing the core tasks of authentication. It first authenticates the partner and MISP to verify their legitimacy, then validates the UIN/VID submitted by the resident. For valid UIN/VIDs, the service processes the resident's input parameters, verifies the OTP, and matches the demographic and biometric data. Based on these checks, it generates either a success response if all modalities match or a failure response otherwise.

Finally, the **Response** section describes the notification services that communicate the authentication outcome to the resident. Depending on the resident's configured preferences, the system sends notifications via email or SMS in their preferred language, ensuring transparency and usability. Overall, the diagram effectively captures the flow of the authentication process in MOSIP, emphasizing secure communication, accurate validation, and user-centric notification mechanisms.

1.3.2 Types of Biometrics

Different kinds of biometrics: Nations intending to adopt biometric recognition for purposes of deduplication and/or authentication have several biometric traits (or “modes”) to choose from. Generally, biometrics can be categorized into two main types: Biological: fingerprints, facial recognition, iris patterns, veins, and so on. Behavioral: keystroke dynamics, walking patterns, signatures, voice recognition, etc. This section offers a succinct comparison of the key biological biometrics utilized in national-scale identification systems for biometric recognition [12].

1.4 Decentralized Identity Management Model

The decentralized identity model is independent of central authority and mainly focuses on the identity owners. This evolving technology leverages Distributed Ledger Technology (DLT) [6]. DLT is a secure record system that performs chronological transactions in a decentralized peer-to-peer network maintained by the volunteered participants [6]. The model overcomes the disadvantage of a single point of failure because the participants maintain copies of the ledger, ensuring privacy requirements [6]. The model helps in portable identity providing end-users with the ability to grant consent to share information. It relies on Blockchain decentralized technology with the append-only mechanism. The requirements for identity such as decentralization, integrity,

immutability, nonreputability, anonymity and transparency are met with blockchain. These models could be public, private or hybrid with varied consensus mechanisms. This paves a pathway for Self-Sovereign Identity [6]. Based on the [16] MOSIP is considered a centralized Identity Model.

1.4.1 Technology Architecture and Methods

Hosting Alternatives: Considerable computing resources are required to store and manage identity data (e.g., in response to identity verification requests), and there are several choices for hosting this infrastructure. Important considerations include: Who manages the physical facilities ("datacenters") that contain the IT infrastructure, supplying power, cooling, physical security, network connectivity, etc.—the ID authority, another government entity, or a private sector provider. Whether the infrastructure is dedicated solely to the ID system (known as "single-tenant") or is part of a shared pool of resources that multiple clients can access on-demand (referred to as "multi-tenant" or "cloud" computing) [27]. A dedicated datacenter run by the ID authority. Some nations opt to store data and applications internally by utilizing dedicated datacenters. This choice affords complete control over every aspect of the ID system, including physical facilities and access, hardware, software (operating systems, applications, technical services), and data. However, it also places a substantial burden on the ID authority to handle all responsibilities and both capital and operating costs for these components, as well as to ensure that there is sufficient technical expertise to support ongoing operations and maintenance [27]. A shared datacenter managed by another government agency. Alternatively, a datacenter operated by a central IT ministry or similar entity can be employed for shared hosting services [27]. Colocation. In this setup, the shared datacenter operator supplies the space, power, physical security, and network connectivity. The ID authority is responsible for providing, configuring, and operating its own infrastructure (servers, storage). As a result, the authority takes on the capital expenditures for its infrastructure, the allocated costs for power and space, and the staffing and operational expenses for maintenance [27]. Managed hosting. In this arrangement, the datacenter delivers and manages the IT infrastructure, along with the physical facility where it is located, in a "single tenant" configuration created for and dedicated to the ID authority [27]. Government ("private") cloud. In the cloud configuration, the datacenter operator is accountable for all physical facilities and IT infrastructure but utilizes modern "virtualization" technologies to aggregate this infrastructure and make it accessible on a flexible, pay-per-usage basis to various clients [27]. Shared datacenter

operated by commercial entities. Private companies also provide infrastructure hosting using the same models previously described—colocation, managed hosting, and multi-tenant cloud [27]. Hybrid approaches. It is feasible to integrate different components of the models mentioned above into a hybrid solution [27].

1.5 Motivation of the Study

The motivation behind this study as my deep interest in cyber security. Especially i want to contribute to data privacy and protection of sensitive data. The other thing is national identity system can play significant role in different aspects the collective information helps the government to tackle poverty and improve the services to the community. But having collected data in centralized manner can impose a highly critical security risk in privacy and data security. As I have been working in cyber security area and as I, the opportunity to execute projects in different governmental and non-governmental organizations i have observed first had how sensitive data and information's are handled and the technologies deployed are insufficient to protect those critical data and information. The other motivation is the main focus in the area is focused on the data security at rest and at transit. i believe that data security at data processing or execution stage doesn't get enough attention and it is not a focus area for protection so, that will impose significant risk as it can be weak point for the attackers to infiltrate in to sensitive data and information. My focus on this area could have significant impact to improve the security of the identity managements systems such as MOSIP.

1.6 Statement of the problem

Biometric-based identity management systems are increasingly employed to ensure secure and efficient user identification. However, these systems, particularly in the context of centralized databases and large-scale enrollments, face critical challenges related to both security and performance. One of the significant concerns is security concerns during the decryption and matching process. The decryption process in traditional (centralized) identity management systems during biometric template matching poses a significant security risk across the enrollment, registration, and authentication phases. This is because biometric data must be decrypted before performing feature comparison, thereby exposing sensitive information. This vulnerability increases the risk of potential attacks, as adversaries can exploit weaknesses in the system to extract

biometric data during the decryption and matching processes [4]. Furthermore, attackers can exploit weaknesses in the decryption process to obtain minutiae features, compromising the privacy and integrity of the biometric data [3]. This makes securing the decryption and matching process essential to protecting user data.

Software-based SDKs inherently carry the risk of security vulnerabilities due to the expected number of bugs per line of code, which, even at an industry benchmark of 0.5–1 defect per KLoC as per [92], can result in exploitable flaws in critical biometric operations. These defects can lead to unauthorized access, data breaches, or the bypassing of security mechanisms, especially in large-scale deployments handling sensitive biometric data.

In addition to Security challenges, there are also significant security concerns during the 1 matching (one-to-many) and deduplication stages, particularly in systems utilizing SDK for enrollment in the initial phase with minimal amount of dataset and ABIS (Automated Biometric Identification Systems) for enrollment processing with vast datasets after millions of registrations. In centralized systems, as the number of templates (N) increases, performance degrades due to the extensive computational resources required to process such a large number of biometric templates. The database must often be partitioned into smaller subsets, where feature samples are only matched to templates stored within a particular partition or indexed using optimized data structures. However, as the volume of data increases, the time and resources required for matching become unmanageable, leading to latency issues, reduced system efficiency, and performance bottlenecks [40][8].

Moreover, centralized identity systems are inherently vulnerable to data breaches. Centralized identity providers represent a single point of failure, where a breach could compromise the entire system's integrity [63]. The lack of transparency and security in these centralized frameworks often leads to issues of unauthorized access, data leaks, and privacy violations [64]. These vulnerabilities are particularly evident in identity management systems such as MOSIP, where security challenges arise from API vulnerabilities, improper data handling, and insufficient token revocation mechanisms, all of which leave sensitive biometric data exposed to risks [29][30].

The central aim of this research is to address critical security and performance challenges in biometric-based identity management systems, focusing specifically on the decryption and matching processes enrollment, registration and Authentication Phases. This research seeks to mitigate security vulnerabilities associated with decryption, which expose sensitive biometric data to potential attacks, and to enhance performance in one-to-many (1) matching and deduplication operations, which become increasingly demanding as the dataset grows in scale. By improving the security and efficiency of these processes, particularly within centralized systems handling large-scale biometric enrollments, this study aims to support secure and effective biometric identification even in environments with vast amounts of stored data and millions of registrations. Additionally, the research explores transitioning toward more secure and decentralized frameworks to reduce the risks inherent in centralized identity systems.

1.7 Research questions

1. What are the specific vulnerabilities associated with sensitive data processing in MOSIP?
2. How to enhance the security on the identity management system - MOSIP?
3. How to improve the performance of the identity management system?

1.8 Objective of the Study

1.8.1 General Objective:

The overarching goal of this research is to enhance the security of sensitive data processing within MOSIP by leveraging Intel SGX for secure biometric decryption and matching, and to improve the performance of the identity management system by proposing a decentralized hybrid architecture.

1.8.2 Specific Objectives:

- Identify and Analyze Vulnerabilities
- Evaluate Existing Deployment Models
- Develop and Test SGX-Bioshield Security Solution
- Evaluate the Performance overhead
- Propose a Decentralized Hybrid Architecture for Performance Enhancement

1.9 Contribution of the study

This research advances the field of identity management by addressing key security and performance challenges in large-scale biometric systems, particularly within the context of MOSIP. It provides a detailed analysis of the security vulnerabilities in MOSIP, specifically focusing on the decryption and matching phases, and proposes an innovative solution leveraging Intel SGX enclaves to securely process sensitive biometric data. The integration of SGX enhances the confidentiality and integrity of biometric data, mitigating risks associated with potential attacks during decryption and template matching.

Additionally, the study proposes a hybrid decentralized architecture to tackle performance bottlenecks in centralized systems, improving scalability and reducing latency in large-scale biometric enrollment and matching. By combining SGX-Bioshield security and decentralized technologies like blockchain, IPFS, and fog computing, this research not only strengthens the security of identity management systems but also optimizes their performance for handling millions of records. The findings contribute to the knowledge base of open-source identity management systems, offering new insights into the application of SGX and decentralized architectures. These contributions are valuable for governments and organizations aiming to implement secure, efficient, and scalable identity management systems, particularly in high-volume contexts such as national ID programs.

1.10 Scope/delimitation of the Study

This research focuses on identifying and analyzing vulnerabilities in MOSIP related to sensitive data processing and performance limitations. The study includes designing and implementing an SGX-Bioshield solution and evaluating its security effectiveness, with the assumption of SGX as a secure device based on existing literature. It also includes developing a hybrid architecture aimed at improving the performance of the existing centralized system. Broader policy or governance issues related to identity management fall outside the scope, as does exploration of alternative hardware-based security solutions.

The research was conducted under significant constraints. Limited resources necessitated the use of SGX1 on a desktop-based machine in a minimized test environment, and the experiment itself was time-bound, focusing on memory-based attacks of limited duration to test security effectiveness. The assessment of Ethiopia's National ID system primarily relied on document reviews, as well as input from four experts: two security experts through interviews and two technology experts via questionnaires. Given their intensive involvement in the national ID project, the experts had limited availability, impacting the depth of assessment feedback. These constraints place limitations on the study's generalizability, as the results are based on a reduced scope of experimental conditions and expert input..

1.11 Structure/organization of the document

The **Introduction** (Chapter 1) provides the foundational background for the study, explaining the motivation behind the research. It defines the research problem, outlines the key research questions, and states the objectives that the study aims to achieve. Additionally, the chapter highlights the significance of the research, its scope, and the delimitation, providing a clear framework for the study.

The **Literature Review** (Chapter 2) explores related work and existing literature relevant to the research problem. This chapter contextualizes the study within the broader field by analyzing prior research, identifying gaps, and justifying the need for the proposed approach.

The **Proposed System** (Chapter 3) focuses on the integration of Intel SGX with the Modular Open-Source Identity Platform (MOSIP) and the development of a hybrid architectural solution. It provides detailed insights into the design and functionality of the proposed system, emphasizing its role in addressing the research problem.

The **Experiments and Results** (Chapter 4) describe the experiments conducted to evaluate the proposed system. This chapter presents the methodology, experimental setup, and the outcomes obtained, offering a comprehensive account of the testing process.

The **Results and Discussion** (Chapter 5) delves into the analysis of the experimental results, interpreting their significance in the context of the research questions and objectives. It provides a

critical discussion on the findings, their implications, and how they contribute to advancing knowledge in the field.

The **Conclusion and Future Work** (Chapter 6) summarizes the key findings of the research and discusses their broader implications. This chapter also identifies potential areas for future exploration, suggesting how the work can be extended to further enhance identity management systems.

The **References** (Chapter 7) compile all the sources cited throughout the thesis, formatted according to the specified citation style (e.g., IEEE format). This ensures proper acknowledgment of prior work and adherence to academic standards.

Finally, the **Appendices** (Chapter 8) include supplementary material that supports the main content of the thesis.

CHAPTER TWO

The literature review section you provided is quite comprehensive and detailed. It covers various aspects of identity management (IDM) security, including the role of biometrics, API security, deployment architectures limitations and the challenges faced by current systems, and potential solutions.

2 Literature Review

2.1 Identity Management and MOSIP

Identity management systems are crucial in the digital age, enabling secure and efficient management of individual identities. These systems are particularly significant for governments and organizations managing vast amounts of sensitive personal data [17]. Identity management systems facilitate the secure handling of user identities, ensuring that individuals' personal information is protected while providing access to necessary services. MOSIP, an open-source platform, offers a modular approach to identity management, allowing for flexibility and customization to meet various needs. In the MOSIP system, identifiers are alphanumeric digital handles used to represent a person's identity through biographic and biometric attributes. The Unique Identification Number (UIN) is a permanent, non-revocable identifier that is randomized to ensure privacy. The Virtual ID (VID) is an alias identifier used for authentication, designed to expire and be privacy-friendly, ensuring it is not linkable. The Application ID (AID), previously known as RID or PRID, is assigned during events like ID issuance or updates. The Token ID (PSUT) is a unique reference number used by partners for identifying users but is not accepted for authentication. Uniquely identify the person; the identity is referred to using identifiers [60].

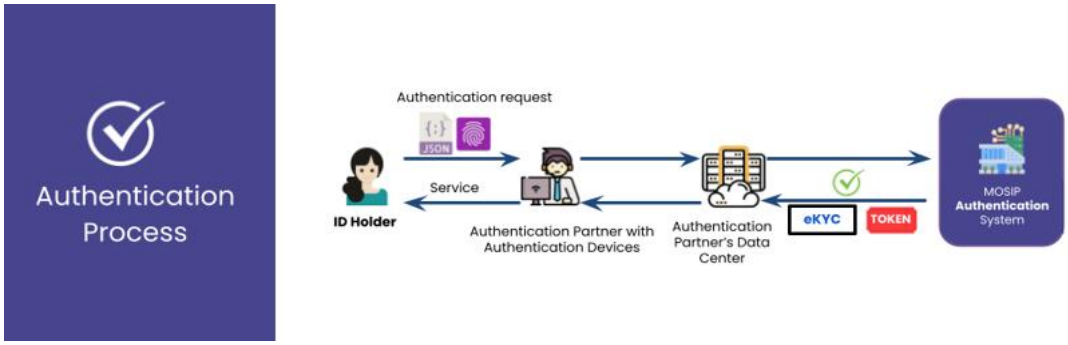

Figure 5. MOSIP Authentication Process [60]

The ID Authentication (IDA) module within MOSIP functions as a standalone service aimed at facilitating smooth identity verification utilizing information from any system. It accommodates various authentication methods, such as OTP generation, biometric checks, and demographic verification. To bolster security and simplify the process, MOSIP suggests the use of eSignet, a solution that incorporates the IDA module to deliver secure and integrated identity verification across both public and private sectors. This approach ensures adherence to MOSIP's security standards and minimizes the necessity for multiple authentication methods.

MOSIP adopts a centralized method where the Identity Provider (IP) and Service Provider (SP) function autonomously. The IP is tasked with supplying end users with identifiers and credentials for multiple SPs as needed. It utilizes Single Sign On (SSO) to facilitate the authentication of the same user across different services. By providing a unique identification and credential within a clearly defined security domain and policy, it streamlines the signing process. Nonetheless, SPs face the risk of depending on a single identity provider, which could be a target for attacks and hacks [19].

MOSIP was developed to deliver an open-source foundation identity system based on open standards, equipped with identity lifecycle management and verification features. Governments can leverage MOSIP to create their own national digital identity frameworks [19]. It provides a modular, flexible, and scalable architecture for building a comprehensive foundational identification system, with a strong emphasis on data protection, privacy, and confidentiality [19]. The MOSIP Logical View Architecture illustrates the workflow stages, which include request initiation, encryption, demographic or biometric data validation, and secure authentication through MOSIP's APIs. This detailed overview clearly explains how authentication functions within the

platform [2]. It demonstrates the interaction among various components such as the authentication client, partner system, and the MOSIP kernel. Furthermore, the architecture incorporates auditing, underscoring security measures and ensuring interoperability among registered biometric devices and trustworthy partners [2].

MOSIP offers a variety of authentication methods, such as Yes/No authentication, KYC verification, and multifactor authentication. These methods support various factors, including biometrics, OTPs, and demographic data, allowing for flexible identity verification based on transaction needs. The authentication system operates on a 1:1 matching principle, and identifiers like UIN or VIDs are used to authenticate individuals. Additionally, MOSIP includes features like tokenization for anonymous verification, consent management, and hotlisting to prevent identity misuse. These capabilities ensure secure, privacy-respecting, and reliable identity authentication for all users [60].

The Indian government established the Unique Identification Authority of India (UIDAI) to issue unique identification numbers called Aadhaar. Aadhaar was planned to reach each citizen based on demographic and biometric data, including fingerprints and iris scans. It aimed to streamline government services, making it easier for citizens to access various benefits. Through Aadhaar, a centralized system was created to manage identity data across the entire population, allowing citizens to authenticate for services with a single identity.

However, as Aadhaar adoption increased, significant security and privacy concerns emerged. These included risks of unauthorized access to sensitive personal information, data breaches, and misuse of biometric data. These challenges have raised questions about data protection and secure authentication methods in India's largest digital identity program [42].

Aadhaar's features make it a distinct and efficient digital identity. Five primary features define Aadhaar's advantages: it is distinctive, as biometric and demographic de-duplication ensure a unique identity for each individual, preventing duplicated entries [42]. Its availability allows for nationwide authentication through online services, offering portability for individuals who relocate. Aadhaar numbers are randomly generated, focusing only on biometric and demographic details while excluding caste, religion, and other personal attributes [42]. The centrally managed

architecture is scalable, supporting up to 100 million daily authentications while maintaining a unified data structure across India. Lastly, Aadhaar uses open-source technologies, enabling flexibility and scalability independent of specific hardware or software dependencies [42].

Aadhaar has thus become essential for various applications, including passport issuance, banking, LPG subsidies, and e-KYC services, although its implementation continues to struggle with security challenges [42]. The Aadhaar authentication service only responds with a yes/no answer and does not return any personally identifiable information as part of the response. This authentication provides a convenient mechanism for all Aadhaar holders to establish their identity. It serves as a platform for identity authentication and can be used to deliver services effectively to Aadhaar holders across the country. The report listed the changes in version [43] from version [44].

2.2 IDM and Security

Nowadays, security is a key requirement in a network environment. Identities are everywhere, and with the growing identity theft, secure identity management has become more relevant than ever. Robust, inclusive, and responsible identification systems can increase access to finance, healthcare, education, and other critical services. They are also essential for improving efficiency and enabling innovation for both public- and private-sector services, such as greater efficiency in the delivery of social safety nets and facilitating the development of digital economies [5]. Identity and access management (I&AM) is the umbrella term for managing users and their permissions, which are necessary for users to access different services.

These services can either be provided by their home organization, like a company or university, or by external service providers [31]. Many ID systems collect fingerprints, iris scans, facial images, and other biometric data for recognition—automatic identification of individuals based on their biological or behavioral characteristics [5]. To understand the various identity management approaches and uncover gaps, several key requirements have been identified, including Usability, Interoperability, Functionality, Trustworthiness, Security, Mobility, Privacy, Law Enforcement, and Affordability [32].

Although biometric systems have been effectively deployed in several civilian applications, they are not flawless. For an ID management system, consistent person recognition is a critical component [33]. Biometrics offer a natural and reliable solution to identity verification by distinguishing individuals based on innate physiological and/or behavioral characteristics. However, the design of a highly secure user-authentication system remains unsolved [34]. In digital ID management, biometrics are increasingly popular because they establish a one-to-one correspondence between individuals and identity records, thus linking people to one record or records to one person. While biometrics are powerful for identity management, they also raise significant privacy concerns for data subjects [34].

Authentication is the process of verifying an identity claim against registered identity information, such as a personal identification number (PIN), password, biometric data (e.g., fingerprint or photo), or a combination of these.

Common security challenges in identity management systems include unauthorized access, data breaches, and privacy violations. These challenges can arise from insecure APIs, inadequate data anonymization, and side-channel attacks [35]. It is critical to emphasize secure data handling practices to prevent data leaks, which can result from improper logging or insufficient anonymization. Side-channel attacks, in which attackers exploit information leakage during data processing, are another major threat. These attacks can reveal sensitive data by analyzing timing variations or power consumption patterns during processing operations [36]. Additionally, the challenges associated with revoking compromised virtual IDs or tokens are significant, as these need to be invalidated to prevent unauthorized access. Effective revocation mechanisms are essential for maintaining the integrity and security of identity management systems like MOSIP [30].

Furthermore, there is a need to investigate data leak prevention strategies in identity management systems, particularly regarding improper logging and poor anonymization practices. Strict data handling protocols are necessary to safeguard sensitive information [35]. In parallel, mitigating side-channel attacks remains a priority, as attackers can exploit subtle processing cues to uncover sensitive data, highlighting the importance of protecting data during processing [37].

The MOSIP ID authentication module has a significant weakness in the confidentiality and authenticity of user credentials, as these credentials are passed to the relying party, granting them access to user data. This introduces privacy risks, as a malicious relying party could misuse or steal user credentials. Although one-time-passwords are limited to single use, nothing prevents the relying party from requesting multiple passwords under false pretenses. Biometric authentication is more secure against this type of attack, as the registered device encrypts biometric data, protecting it from unauthorized access. However, the encrypted biometric data can be reused by the relying party in the absence of a nonce, making it a potential vulnerability [38].

API security in identity management systems must be robust, with strong authentication and authorization mechanisms to prevent unauthorized access to data, especially in platforms like MOSIP. This need for secure APIs forms the basis of further research into secure implementations in MOSIP [17]. Additionally, Zero-Knowledge Proofs (ZKPs) have the potential to enhance privacy in identity management systems. However, their implementation needs to be fortified to avoid compromising user data confidentiality [29].

Patel and Singh [39] discuss the importance of data provenance and auditability in open-source identity platforms like MOSIP. Their research emphasizes the need for effective data governance to ensure transparency and accountability in sensitive data management.

Biometric systems can utilize a range of biometric traits, including fingerprints, facial recognition, iris patterns, and vein patterns (biological) as well as keystroke dynamics, gait, signature, and voice patterns (behavioral). This part compares the main biological biometrics employed in national identification systems for the purpose of biometric identification. Authorization occurs after identity verification and involves establishing access permissions based on the connection between the individual and the Relying Party (for instance, a bank), separate from the Identity Provider (for example, the National Identification Authority).

MOSIP's data encryption strategy employs external encryption before storage in the database, ensuring that personal identifiable information (PII) remains secure. Integrity is provided via HMAC SHA256 hash, and the data is encrypted with a session key that is backed by a hardware

security module (HSM) key pair, unique to each application or service [38]. The system should also enforce security control across distributed databases and monitor for abnormal behavior [40].

MOSIP is a centralized system, and one of the challenges with this architecture is the creation of a detailed authentication record that could compromise privacy. Systems must be designed to optimize flexibility and user agency, particularly when centralized systems are deployed [41].

Attestation in the context of Intel SGX is a process by which a third party verifies that software is running on an Intel SGX-enabled platform. This ensures that software is protected within an enclave before it can access secrets and protected data. Intel SGX supports both intra-platform and remote attestation, enabling verification of software's integrity and security properties.

2.2.1 MOSIP Biometric SDK

The Biometric SDK is a comprehensive solution used for various biometric-related tasks, particularly in applications such as Registration Client, backend quality checks, biometric authentication during onboarding (internal auth), and ID authentications. The Biometric SDK library enables the Registration Client to perform functions such as 1 matching, segmentation, and feature extraction. The Biometric SDK service is required for 1:1 matching and quality checks of biometric data at the MOSIP backend. This service must be accessible by the Registration Processor and IDA Internal Services and exposes REST APIs as specified in the IBioAPI. A mock service version is provided, which loads the mock BioSDK internally during startup and exposes endpoints for 1 matching, segmentation, and extraction. The service can be deployed in a MOSIP Kubernetes cluster or run separately on a server, with scalability considerations depending on system load, such as the rate of enrolment and ID authentication. The service interacts with the BioSDK library through the IBioAPI, while the BioSDK service API is yet to be defined [60].

The Biometric SDK provides a robust framework for performing critical biometric tasks such as matching, segmentation, and feature extraction, supporting applications like the Registration Client and backend quality checks. With its capability to facilitate 1:1 and 1 matching, as well as biometric authentication, the SDK plays a key role in ensuring the efficiency and accuracy of biometric systems within MOSIP. The service's scalability and deployment flexibility, whether within a Kubernetes cluster or on a separate server, make it adaptable to varying system loads.

While the service API is still to be defined, the mock service version provides valuable testing capabilities, ensuring the SDK's readiness for integration and real-world use.

In the context of MOSIP, each component in the infrastructure plays a crucial role in supporting the biometric registration and authentication process. The Registration Device is located on-site with the Registration Client and captures biometric data during enrollment, which is then transmitted to the Secure Biometric Interface. This interface, embedded in both the Registration Client and Authentication Client, ensures secure capture and transmission of biometric data, including signing and encrypting the data to maintain its integrity. The BIO SDK, located in both the Registration Client and MOSIP Backend, performs quality checks, de-duplication, and operator authentication during the registration process. In the backend, it handles further quality checks and de-duplication for 1 matching and performs 1:1 authentication during the ID verification stage [60].

The REG CLIENT, situated on-site during registration, acts as the primary interface for capturing, signing, and forwarding biometric and demographic data packets to the MOSIP Backend. The REG PROCESSOR, within the MOSIP Backend, processes these packets, performs additional quality checks, and handles de-duplication and 1 matching before storing the data in the backend. The ID AUTH component, also within the backend, provides identity verification during authentication and performs 1:1 matching against stored biometric data using the BIO SDK. The ABIS, deployed in a secure environment, handles large-scale 1 de-duplication to ensure each biometric record is unique, with the REG PROCESSOR interfacing with ABIS during registration [60].

The Authentication Device, on-site with the Authentication Client, captures and verifies biometrics during the authentication process. The Foundational Trust Module (FTM), integrated into the Secure Biometric Interface on the Authentication Client, adds an extra layer of trust by ensuring the authenticity and tamper-proof nature of captured biometric data. The AUTH APP, deployed on the Authentication Client, initiates the authentication request and securely sends encrypted biometric data to the MOSIP Backend. Finally, the Device Management Server, part of the MOSIP Backend, manages device registrations, key rotations, and de-registrations, providing encryption certificates to ensure secure communication and data integrity throughout the process [60].

2.3 SGX based solutions

Software Guard Extension (SGX) is a new security technology proposed by Intel Corporation. It provides a trusted isolation space for the computer platform, maintaining the integrity and confidentiality of user code or data [45]. At present, this technology has been widely used in the field of cloud computing security protection [45]. The implementation of cryptographic algorithms faces many serious security risks. Attackers can damage the running environment and obtain keys through the operating system, posing a serious threat to the security state of the environment [46]. SGX, an extension of Intel's instruction set, protects the security of programs during execution [26].

Intel SGX has started to be widely adopted. Cloud providers like Microsoft Azure, IBM Cloud, and Alibaba Cloud are offering solutions that implement data-in-use protection via SGX. However, SGX also has obvious shortcomings. The biggest drawback is that developers need to refactor the code and divide the program into trusted and untrusted parts. Currently, Intel has released an SDK to assist with this, but the work required is still heavy and can easily lead to security leaks. To address these security insecurities and further improve performance, different approaches have been tried to keep the program intact within the enclave, avoiding code refactoring. Notable efforts include Haven, SCONE, and Graphene-SGX [47],[48].

Additionally, side-channel attacks, such as cache attacks, can lead to sensitive information leakage, demonstrating that SGX still has room for improvement [49]. Research on SGX is still in its developmental stage and has not reached maturity. Moreover, users often lack a deep understanding of SGX technology, making it a challenge for them to fully utilize it. Our goal is to collect and summarize different literature to demonstrate the existence and evolution of research in this area. By searching, classifying, analyzing, and summarizing relevant papers, we provide an overview of SGX's applications, attack methods, and improvements, with a primary focus on its applications [49].

After preliminary analysis, we found that SGX is widely applied in cloud security. For example, SGX has been used to build a fully isolated execution environment for cloud applications [47] and to construct a secure, trusted computing environment for cloud-based big data [50]. Intel Trusted

Execution Technology (TXT) is a precursor to SGX, focusing on establishing a stable environment using specific Intel CPUs, dedicated hardware, and related firmware. This allows system software to achieve a more secure system and better data integrity [49]. Based on TXT, Intel proposed SGX, which creates enclaves that function as trusted execution environments (TEEs). SGX was first introduced at the HASP conference in 2013 [51].

Intel officially released SGX2 in 2016 and introduced a physical CPU (Skylake) that supports SGX for the first time [52]. SGX offers a unique execution environment with confidentiality and integrity protection [53], allowing an application (or part of it) to execute in a secure container called an enclave. The application is divided into trusted and untrusted parts based on the needs. Sensitive data and related functions are placed in the enclave, while external access to it is forbidden to protect it from potential attacks. Sensitive functions are processed in clear text inside the enclave. The results of these operations are fed back to the outside, while the involved data remains in trusted memory space. The enclave and associated data structure are stored in the protected CPU memory Enclave Page Cache (EPC), with each EPC assigned to a single enclave. Access to code and data within the enclave can only occur through a specific interface. The CPU prevents non-enclave access to the processor's reserved memory, and any unauthorized external access will lead to an aborted transaction. Thus, the areas exposed to attacks are greatly reduced, providing a safer environment for private data. Unlike other TEE systems, which have large trusted computing bases (TCBs), SGX provides a small TCB that only includes the CPU and enclave [54].

In summary, the security aspects of Intel SGX consist of the following: 1) the application is partitioned into two segments: Trusted and Untrusted. 2) Operations involving sensitive data are contained within an enclave. 3) The untrusted segment must create and invoke the enclave function to access sensitive information. Only internal code within the enclave has the ability to view its data, and any external access is consistently denied. Once the call is complete, the data in the enclave is cleared from protected memory [54].

When evaluating Intel SGX, it can be compared to other Trusted Execution Environments (TEEs) like ARM TrustZone and AMD Secure Encrypted Virtualization (SEV). These TEEs are well-known and possess distinct advantages. Table 1 presents the primary characteristics of these three TEEs, comparing them across three dimensions: Key technology, CPU division, and application

complexity. Key technology refers to the specific implementation techniques, CPU division outlines the segmentation of the CPU and other modifications, while application complexity highlights the technical challenges associated with utilizing these TEEs [54]. Since the introduction of SGX technology in 2013 and its official release in 2016 with SGX2, research on its application and improvement has increased, and the number of related papers continues to grow [54].

TrustZone and SGX differ in their mechanisms. TrustZone divides the CPU into secure and non-secure parts, where the supervisor manages the flow of data between them. SGX, on the other hand, has a stricter requirement, completely isolating the execution environment and resources. Access to memory regions must be controlled on a case-by-case basis, with security maintained by the application itself. This makes the coding process more difficult and requires developers to have a solid understanding of security principles and programming. While SGX offers excellent security features, it also has specific shortcomings [54].

SEV and SGX technologies have slightly different areas of emphasis, yet both offer secure and trusted environments for execution. SEV safeguards virtual hosts from potentially harmful cloud service providers by encrypting data in physical memory. In contrast, SGX delivers detailed protection at the application layer, but it does not encompass all untrusted components within the enclave. Mofrad et al. [36] evaluated the security and performance of SGX versus AMD, determining that SEV is superior to SGX for encrypting and safeguarding extensive data, while SGX is more dependable for protecting memory data [37].

Despite these strengths, SGX has practical weaknesses. Developers need to reconstruct code and divide the program into trusted and untrusted parts, which can be a complex and difficult task. Additionally, constructing the enclave can impact system performance, causing bottlenecks in data processing and security protection. SGX can lead to performance losses due to factors such as enclave conversion costs, system-level function access, and large amounts of EPC page replacement [37].

To maintain a small TCB while achieving code privacy and integrity, SGX encryption is an excellent choice. Iron, a practical function encryption system using SGX, enables secure

calculations on encrypted data at full processor speed. Iron employs a Key Manager Enclave (KME) that manages the master key and provides decryption permission for specific functions. After decryption, the Decryption Enclave (DE) processes the data and clears all relevant state from memory [55].

Iron performs well with complex functions and outperforms known solutions for simple applications. The authors also demonstrated its security by modeling the encryption function in the context of hardware elements, proving that Iron meets the security model [56]. An SGX encrypter was designed to protect IP in executable files on Windows from malicious static or dynamic analysis. This study uncovered critical issues with SGX programming mode and performance, revealing the need for optimization. The SGXTuner tool, presented in the study, helps improve SGX application performance through stochastic optimization, improving execution times without compromising security [56].

2.4 Hybrid Architecture

New frameworks are emerging iteratively [59]. To the best of our knowledge, this paper reviewed by listing some of the most applicable digital identity-based solutions by giving mechanism, digital identity solution, feature, and comparison between these models [59]. The paper also called this digitizing world an era of Industrial internet and expressed the time is for decentralized Identifiers (DID) by illustrating some of the milestones in the internet digital identity evolution path [81].

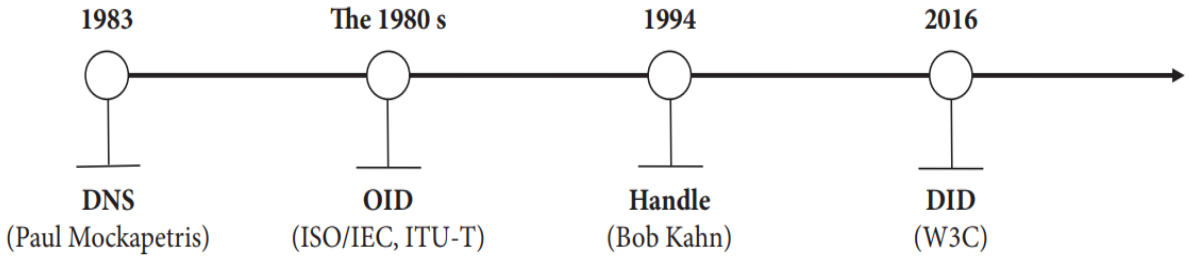

Figure 6. Some of the milestones in the internet digital identity evolution path

The Modular Open Source Identity Platform (MOSIP), developed by the International Institute of Information Technology, Bangalore, provides the technical foundation digital ID system, ensuring that it is scalable, customizable, and supports minimal data collection, with data encrypted at all times to safeguard privacy [7]. Registration is free, and the system is easy to maintain with built-

in monitoring and auditing mechanisms [7]. The table provided by [60], evaluated the three Architectural approaches.

In evaluating hosting options for identity management systems, there are several models to consider, including centralized, federated, and decentralized architectures. Key decisions involve who operates the infrastructure, whether the system uses single-tenant or multi-tenant solutions, and whether to rely on government or private-sector datacenters. Various options include dedicated datacenters, colocation, managed hosting, and cloud-based services like IaaS or PaaS. Flexibility, scalability, and security are essential considerations, with hybrid approaches combining different models to optimize resource usage and resilience across systems. Additionally, interoperability and technical standards are critical for efficient system integration [12].

Federation is a set of agreements, standards, and technologies that a group of service providers can use to identify the users from other domains [65]. Different identifiers owned by the same user are mapped together in different domains. This allows the user to work across domains without repeated authentication. This model also supports single-sign-on across multiple domains. Every Service Provider can store user identities locally and have its own identity database. Policies and requirements of different groups vary, which may cause disagreements among service providers [65]. This model resembles the user-centric model because power is shared between multiple central authorities [65].

In cryptocurrencies, a blockchain serves as a decentralized database that records all transactions. The network, rather than a central entity like a bank or government, continuously verifies its integrity. Federated identity management systems can provide authentication and authorization capabilities across organizational and system boundaries [66]. It requires agreements that an identity at one provider is recognized by other providers and contractual agreements on data ownership [66].

In distributed systems, multiple computers interact over a network to perform data processing operations in parallel [67]. Systems can be set up with different combinations of replications, and data partitioning can be performed using sharding to enhance scalability, consistency, and fault

tolerance. The study [1] highlights that IPFS uses a peer-to-peer (P2P) network model for file sharing, which is decentralized and distributed across multiple computers or nodes. Files are split into parts and stored in a network of nodes that track the file by hash, allowing the original file to be reconstructed when the parts are assembled.

The implementation of Distributed Hash Tables (DHT) for the storage and retrieval of files represents a significant advancement for IPFS. It saves files on a blockchain in the form of key-value pairs. The data is divided into chunks of 256 KB and distributed across a network of nodes or computers. This organization facilitates efficient access and retrieval among nodes. In contrast to BitTorrent, which depends on torrents, IPFS utilizes a hash ID that directs to a specific file [1]. In distributed systems, load balancing ensures that tasks are evenly allocated across resources to prevent bottlenecks and enhance performance [68].

Distributed systems offer higher throughput and response rates compared to centralized systems due to their modularity. They can be scaled horizontally (adding more nodes) or vertically (increasing processing power of each node) to handle larger data volumes. Redundancy in distributed systems ensures that failure in one part of the network won't affect the overall system, enhancing resilience [67].

Blockchain is a type of Distributed Ledger Technology (DLT) where transaction records are stored in blocks across nodes. The computational power of the network is distributed, resulting in improved performance. Blockchain enhances security, speeds up disbursements, and ensures consensus. Once a transaction is verified, it gets a unique hash ID and is added to the ledger. After being added, it cannot be altered or deleted [1].

Blockchain authentication verifies users, transactions, and messages via smart contracts deployed to the blockchain [66]. A Smart Contract Authentication (SCA) layer can automatically execute authentication whenever required, eliminating the need for a third party. This reduces costs while enhancing security and privacy [66].

Furthermore, the Interplanetary File System (IPFS) uses a peer-to-peer (P2P) network model for decentralized file sharing across multiple computers or nodes. Files are split into parts and tracked by hash, which enables reconstruction when assembled [1]. The use of Distributed Hash Tables (DHT) for file storage and retrieval is a key innovation of IPFS. It stores files as key-value pairs on a blockchain and allows efficient access between nodes. Unlike BitTorrent, IPFS uses a hash ID to point to a single file rather than relying on multiple torrents. The physical location of the file does not matter, as it is represented by its hash ID in the decentralized platform [1].

Employing Trusted Third Party (TTP) services in the cloud establishes trust and preserves the confidentiality, integrity, and authenticity of data and communication [66]. Public Key Infrastructure (PKI) teamed with TTP provides strong authentication and authorization through public-key cryptography, allowing users to authenticate others without sharing secret information [66]. Single-Sign-On (SSO) is an example of TTP authentication, enabling users to authenticate once and access multiple sites without re-authenticating [66].

Interoperability is essential for creating efficient, sustainable identity ecosystems. It allows different systems, databases, devices, or applications to communicate and transfer data with minimal user intervention [12].

To enable machine-to-machine communication, systems must adopt common technology standards for software, hardware, and platforms throughout the identity lifecycle. Key standards include those related to biometrics, cards, 2D barcodes, digital signatures, and federation protocols. Some standards represent a consensus, while others may vary depending on the design and goals of the ID system (e.g., international travel) [12].

Federated identity management systems enable authentication and authorization across multiple organizations by allowing different service providers to recognize the same user, thereby supporting single sign-on across domains. This model, resembling the user-centric model, involves multiple central authorities instead of one [65].

Blockchain, a decentralized database, plays a key role in cryptocurrencies by recording transactions in a distributed ledger. This network-based verification of transaction integrity ensures enhanced security and faster transaction disbursements. Blockchain's decentralized nature eliminates single points of failure, providing greater reliability and resilience in digital systems [1].

In distributed systems, multiple computers interact to perform parallel data processing. This architecture is highly scalable, ensuring better performance by distributing workloads and optimizing resource use [67]. Distributed Hash Tables (DHT) and IPFS, a peer-to-peer file sharing protocol, leverage this architecture for efficient file storage and retrieval, offering improved scalability and fault tolerance [1].

Blockchain provides enhanced security through consensus mechanisms and immutability, ensuring that once transactions are verified and added to the ledger, they cannot be altered [1]. Blockchain-based authentication ensures that users and transactions are legitimate, verified by smart contracts deployed on the blockchain [66].

Table 1. Centralized vs Decentralized vs Distributed Systems," Berty Technologies, 2019.

Criterion	**Centralized**	**Decentralized**	**Distributed**
Control	Single central authority	Multiple authorities share control	No central control, equal access for all
Fault Tolerance	Prone to single point of failure	More resilient, other nodes continue if one fails	Highly resilient, failure of one node doesn’t affect others
Cost	Low maintenance	Higher maintenance	Initially higher, but shared resources reduce long-term costs
Scalability	Limited by central server capacity	Scalable, multiple nodes can be added	Highly scalable, resources can be added across the network
Privacy	High risk, central owner access	Moderate risk, multiple access points	Higher privacy, data shared across network

Security	High security risk	Moderate risk	Higher security, no single point of failure
Data Integrity	Controlled by one entity	Variations possible across nodes	High, distributed verification
Access Speed	Can degrade under load or failure	Faster for users near active nodes	Fast and consistent due to distributed resources
Setup Speed	Fast deployment	Slower, requires multiple regions	Slow, requires complex setup
Transparency	Low, centralized control	Moderate transparency	High transparency, shared control
Criterion	Centralized	Decentralized	Distributed
Control	Single central authority	Multiple authorities share control	No central control, equal access for all

The Modular Open Source Identity Platform (MOSIP), developed by the International Institute of Information Technology, Bangalore, provides the technical foundation digital ID system, ensuring that it is scalable, customizable, and supports minimal data collection, with data encrypted at all times to safeguard privacy [7]. Registration is free, and the system is easy to maintain with built-in monitoring and auditing mechanisms [7]. The table provided by [60], evaluated the three Architectural approaches.

2.5 Related Work

Considerations for Secure MOSIP Deployment: The paper *Considerations for Secure MOSIP Deployment* [9] focuses on enhancing the security and privacy of the Modular Open Source Identity Platform (MOSIP). It provides an in-depth analysis of threats across three key phases of MOSIP: pre-registration, registration, and authentication, using STRIDE/DREAD threat modeling methodologies. By identifying vulnerabilities in these stages, the paper suggests mitigation strategies that contribute to the development of a resilient identity management system (IdMS) capable of safeguarding user data and fostering trust among stakeholders.

The paper highlights the innovative design of MOSIP, which addresses gaps observed in other global identity systems. A comparison of these systems is presented in Table 1, showcasing the diversity in implementation, benefits, and challenges.

Table 2. A comparison of digital identities in different countries, adapted from [9]

Year	Country	Identity	Description	Advantage	Challenges
1999	Finland	eID	Used as a travel document, to access services, and sign electronically	Unified identity	Interoperability and compatibility across web-based platforms were not defined
2000	Australia	Card eID	Access to financial services with partial privacy-preserving features (e.g., identity)	Technology-agnostic and compatible across smartphones and smart cards	Creation of individual PINs for different organizations
2002	Estonia	eID	Stored users' data providing access to services (banking, voting, etc.)	Key pairs are used to sign information shared with a relying party	Vulnerability exploited (2017), gaining the private key from the public key
2006	Belgium	eID	Mandatory eID card with citizen's photo and personal details	Stored digital signatures and keys	Lack of privacy-enhancing technologies
2009	Sweden	eID	Legislation allowed banks to issue eIDs to access government services	eIDs had two formats: 'soft' ID (digitally stored) and 'hard' ID (card)	Offers less flexibility (migration of user data from legacy to sophisticated systems)
2009	India	Aadhaar card	Distinctive, nationally available, random nature, central architecture with open-source technologies	Two formats: 'soft' ID (digitally stored) and 'hard' ID (card)	Security and privacy issues, data leaks, authentication without consent

The table underscores the need for MOSIP's robust design, as it addresses security and privacy gaps observed in foundational systems like Aadhaar. While Aadhaar has faced criticism for its vulnerability to data leaks and unauthorized authentication, MOSIP integrates privacy-by-design principles, such as data encryption, auditable systems, and zero-knowledge proofs, to mitigate such risks [9].

Through STRIDE/DREAD, the paper categorizes and prioritizes risks. For the pre-registration phase, it identifies threats like SQL injection, identity spoofing, and phishing attacks, recommending mitigations such as input validation, HTTPS with SSL encryption, and continuous database monitoring. In the registration phase, the risks include offline data tampering, unauthorized updates, and ransomware attacks. Suggested countermeasures include employing secure cryptographic techniques, ensuring patch integrity verification, and renewing tokens periodically. The authentication phase faces risks such as replay attacks, biometric data theft, and misuse by relying parties. To address these, the paper recommends biometric encryption, secure credential exchange protocols, and stronger KYC mechanisms [9].

The modular and open-source nature of MOSIP is highlighted as a significant advantage, enabling governments to customize and scale the platform to meet their needs. However, the paper notes challenges, including the evolving nature of threats and the complexities of ensuring privacy in decentralized models [9].

A Comparative Study of Cyber Threats on Evolving Digital Identity Systems: The increasing reliance on digital identity management systems (IDMS) for accessing essential services such as financial transactions, healthcare, and government programs has made them critical targets for cyber threats. The paper *A Comparative Study of Cyber Threats on Evolving Digital Identity Systems* [2] offers a detailed examination of the security challenges facing IDMS and emphasizes the need for robust security frameworks to ensure their reliability and integrity. It categorizes IDMS into foundational and functional identities. Foundational identities, like passports and birth certificates, serve as primary identification forms issued by governments, while functional identities are sector-specific, such as healthcare or driving licenses, and can be linked across multiple services.

A significant contribution of the paper is its use of the STRIDE threat modeling framework, which categorizes threats into six types: Spoofing, Tampering, Repudiation, Information Disclosure, Denial of Service (DoS), and Elevation of Privilege. By applying STRIDE to IDMS, the authors identify critical vulnerabilities, such as identity theft, Sybil attacks, and DoS/DDoS attacks, and emphasize the importance of addressing these threats through robust security measures [2].

The paper advocates for decentralized identity models as a promising solution, though it acknowledges challenges related to digital literacy, rural connectivity, and governance frameworks. Additionally, database security plays a pivotal role in safeguarding sensitive information stored within these systems [2].

Vulnerability Assessment in National Identity Services: The paper *Vulnerability Assessment in National Identity Services* [16] presents an extensive evaluation of security properties, infrastructure, and potential vulnerabilities across various national identity systems, including MOSIP, eID, Login.gov, GOV.UK Verify, and OAuth. These systems form the backbone of digital identity management, enabling individuals to access essential services.

MOSIP is highlighted as a flexible and cost-effective platform designed to help governments implement digital identity systems. Its infrastructure includes key modules: the Kernel, Pre-Registration, Registration, and ID Authentication, each with specific security roles. The paper identifies vulnerabilities within these modules, including potential SQL injection, man-in-the-middle (MITM) attacks, and SIM card swap attacks during pre-registration [16].

Comparative analysis shows that while systems like Login.gov and GOV.UK Verify have strong privacy and security mechanisms, MOSIP's modularity and scalability position it as a promising solution. The paper emphasizes the importance of securing MOSIP's infrastructure to adapt to evolving threats [16].

Conclusion: The reviewed studies collectively underscore the critical need for secure, scalable, and privacy-preserving identity management systems (IdMS) to protect sensitive data in a rapidly digitizing world. The paper *Considerations for Secure MOSIP Deployment* [9] highlights MOSIP's modular architecture and privacy-by-design approach, addressing key vulnerabilities such as identity spoofing, data tampering, and ransomware attacks.

Similarly, *A Comparative Study of Cyber Threats on Evolving Digital Identity Systems* [2] identifies significant vulnerabilities in both traditional and decentralized IDMS, including identity theft and Sybil attacks. The study advocates for robust security frameworks incorporating encryption, multi-factor authentication, and real-time monitoring.

The *Vulnerability Assessment in National Identity Services* [16] further deepens the analysis by evaluating the security properties of various national ID systems, emphasizing the need for proactive defense mechanisms.

CHAPTER THREE

3 Proposed Solution

3.1 SGX-Bioshield -Integration

The proposed architecture is a secure identity management platform designed to handle sensitive operations such as device validation, biometric data quality control, encryption, decryption and biometrics Matching with with high levels of confidentiality and integrity. It integrates SGX-BioShield to securely process data, where encryption and decryption of sensitive biometric and demographic information occur within a trusted execution environment. The Validation and Quality Controller ensures the integrity and quality of biometric data while also validating the devices involved in the registration and authentication processes. Once validated, data is passed to the Registration Module for one-to-many matching or the Authentication Module for one-to-one verification. These processes are supported by a Key Management Service, which includes a Hardware Security Module (HSM) and Key Database (Key DB) for secure cryptographic key management. The platform also interacts with a Database Management Service that connects to secure storage for biometric and demographic data, ensuring robust and scalable identity verification and management.

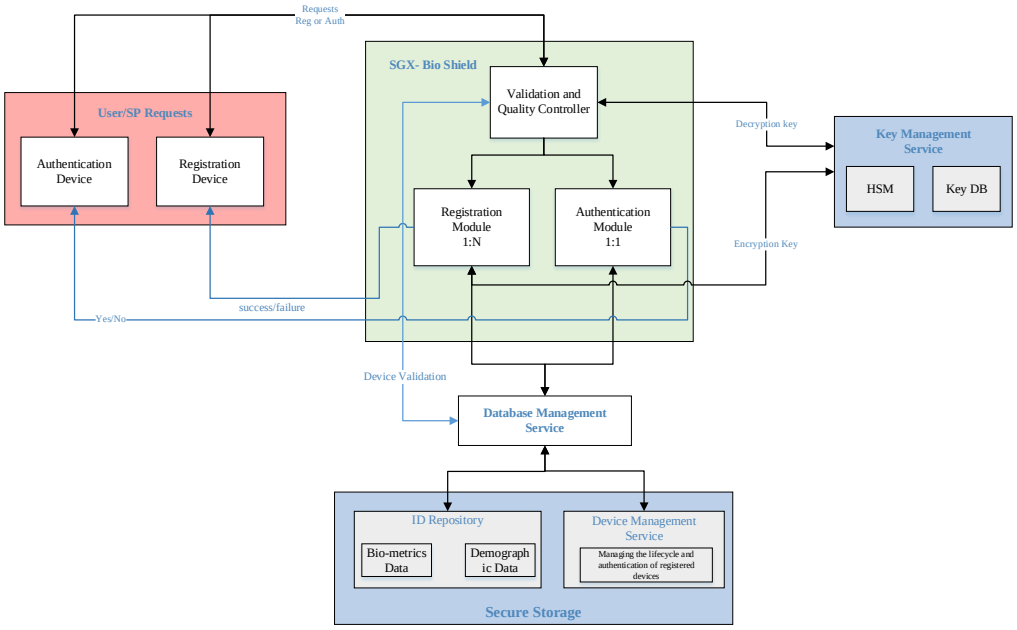

Figure 7. Proposed Platform for Registration and Authentication system

The figure illustrates a potential integration of Intel Software Guard Extensions (SGX) technology within a biometric Registration and authentication system. The design emphasizes secure processing and communication of sensitive biometric data.

Description of Modules and Functionalities

User/SP Requests: - This module represents the interaction points for users or service providers (SP) to request registration or authentication services. Users utilize **Registration Devices** to enroll their biometric and demographic data, while **Authentication Devices** verify the user's identity for subsequent operations.

SGX-Bio Shield: - The core component ensuring secure processing, this section leverages Intel SGX technology for secure execution. It includes the **Validation and Quality Controller**, which checks the validity and quality of data (e.g., biometric and demographic inputs) before passing it to other modules. The **Registration Module** handles multiple (1:N) biometric enrollments, ensuring scalability for a large user base. The **Authentication Module** supports one-to-one (1:1) matching to verify user identity during authentication.

Key Management Service: - This module manages encryption and decryption keys using a **Hardware Security Module (HSM)** and a **Key Database (Key DB)**. It ensures that all cryptographic keys are securely stored and utilized for data encryption during storage and secure communication.

Database Management Service: - This service facilitates the storage and retrieval of biometric and demographic data. It acts as a bridge between the **SGX-Bio Shield** and the **Secure Storage**, ensuring that data integrity and confidentiality are maintained during access or modification.

ID Repository: - A secure storage system for sensitive user data, including **Biometric Data** (e.g., fingerprint, iris) and **Demographic Data** (e.g., name, age, address). This repository is protected with strong encryption mechanisms.

Device Management Service: - This module handles the lifecycle and authentication of registered devices. It ensures that only trusted devices can participate in the registration and authentication processes, mitigating risks of compromised endpoints.

Secure Storage: - The final storage layer for sensitive data, ensuring high confidentiality and integrity. All data in this storage is encrypted using the keys managed by the Key Management Service.

Secure Communication Methods

To maintain secure communication between modules, the following methods and protocols will be employed.

Transport Layer Security (TLS): - Secure communication between devices and the SGX-Bio Shield will utilize TLS 1.3 for encryption, ensuring confidentiality and protection against eavesdropping or man-in-the-middle (MITM) attacks.

Mutual TLS (mTLS): - For interactions between the **SGX-Bio Shield**, **Key Management Service**, and **Database Management Service**, mutual authentication through mTLS will be used to verify the identity of both parties in the communication.

Secure Key Exchange: - Elliptic Curve Diffie-Hellman (ECDH) will be used to securely establish shared keys for encryption and decryption during data transmission.

End-to-End Encryption: - Biometric and demographic data will be encrypted at the source (devices) and decrypted only inside the SGX-Bio Shield to ensure end-to-end data protection.

Intel SGX Remote Attestation: - Remote attestation will verify the integrity and authenticity of SGX enclaves before initiating any data exchange, ensuring that only trusted modules participate in the communication.

Message Authentication Codes (MAC): - To ensure data integrity and authenticity, MACs will be added to all transmitted data packets. Any tampering will be detected upon verification.

API Protocol: - The API facilitates secure communication for registration and authentication requests with the National ID management system interface. It ensures the protection of sensitive data exchanged between the system and the requests. By implementing robust security mechanisms, the API helps prevent unauthorized access, ensuring the confidentiality and integrity of the data. This secure communication framework provides a trusted environment for handling user authentication and registration. It is designed to safeguard data throughout the transmission process. These measures enhance the overall security of the National ID management system.

These secure communication methods will work together to provide a robust and reliable infrastructure for safeguarding sensitive data and protecting user privacy within the platform.

3.2 Proposed Secure Biometric Registration framework

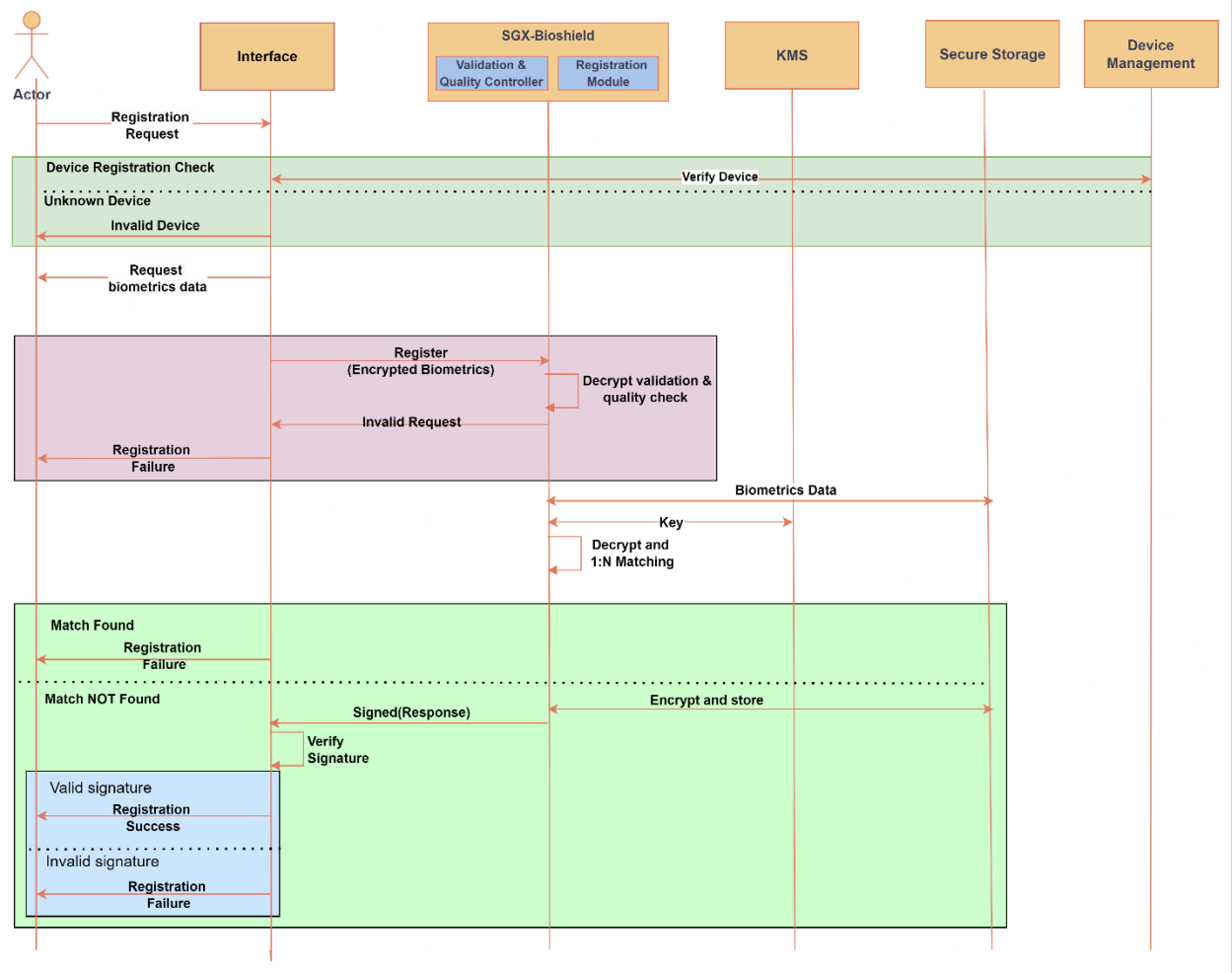

Figure 8. Proposed Secure Biometric Registration framework

The sequential diagram outlines the registration process in a secure MOSIP platform, illustrating the interactions between various components to securely register a user's identity. The steps are as follows:

Registration Request: - The user initiates a registration request through the interface. The request is forwarded to the SGX-BioShield for processing.

Device Registration Check: - The Validation and Quality Controller in the SGX-BioShield verifies whether the requesting device is registered and authorized. If the device is invalid or unknown, an "Invalid Device" response is sent back, terminating the process.

Biometric Data Request: - If the device is valid, the system requests biometric data from the user via the interface. The user provides encrypted biometric data, which is forwarded to the SGX-BioShield for further processing.

Validation and Quality Check: - The Validation and Quality Controller decrypts the biometric data and performs a validation and quality check to ensure the data's integrity and authenticity. If the data is invalid or does not meet quality requirements, a "Registration Failure" response is sent back.

Biometric Data Matching and Key Retrieval: - Once the biometric data passes the quality check, it is sent to the Key Management Service (KMS) to retrieve the encryption key. The SGX-BioShield uses the key to perform 1:N matching to ensure uniqueness within the ID repository.

Match Found or Not Found: - If the biometric data matches an existing record, the registration process fails with a "Registration Failure" response. If no match is found, the system proceeds to verify the signature of the data.

Signature Verification: - The SGX-BioShield verifies the signature associated with the biometric data. If the signature is invalid, the registration fails with a "Registration Failure" response.

Registration Success: - If the signature is valid and the data is unique, the registration is successful. The system encrypts and stores the user's data in secure storage and sends a "Registration Success" response back to the user.

This registration process ensures the security and integrity of user data, employing device validation, biometric matching, and signature verification. It highlights the collaboration between the user interface, SGX-BioShield, Key Management Service, Secure Storage, and Device Management to securely onboard users.

3.3 Proposed Secure Biometric Authentication framework

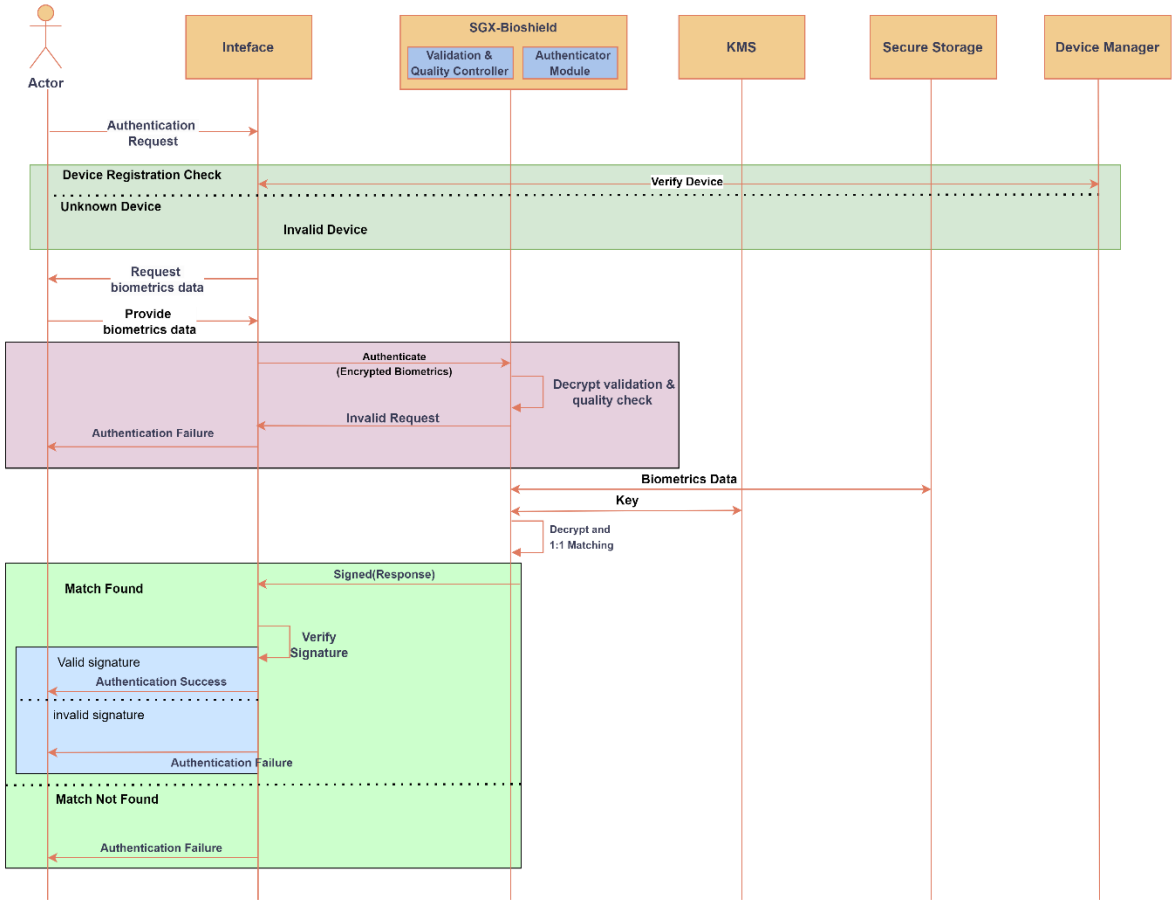

Figure 9. Proposed Secure Biometric Authentication framework

The figure illustrates the authentication process in a secure MOSIP platform, demonstrating interactions between different components to validate and authenticate a user's identity. The steps are as follows:

Authentication Request: - The user initiates an authentication request through an interface. The request is received by the SGX-BioShield, which initiates the process by verifying the device.

Device Registration Check: - The SGX-BioShield forwards the request to the Validation and Quality Controller to verify if the requesting device is registered.If the device is unregistered or invalid, an "Invalid Device" response is sent back, and the process terminates here.

Biometric Data Request: - If the device is valid, the system requests biometric data from the user via the interface. The user provides encrypted biometric data, which is then sent to the SGX-BioShield.

Validation and Quality Check: - The Validation and Quality Controller decrypts the biometric data and performs a validation and quality check. If the request is invalid (e.g., malformed data), an "Invalid Request" response is sent, terminating the process.

Biometric Data Matching: - If validation is successful, the biometric data is forwarded to the Key Management Service (KMS) to retrieve the decryption key. The data is decrypted and sent to Secure Storage for 1:1 matching against stored biometric records.

Match Found or Not Found: - If a match is not found in the records, an "Authentication Failure" response is sent back to the user. If a match is found, the system proceeds to validate the signature.

Signature Validation: - The SGX-BioShield validates the signature of the matched data. If the signature is invalid, an "Authentication Failure" response is sent.

Authentication Success: - If the signature is valid, the authentication process is successful. A signed response indicating "Authentication Success" is sent back to the user via the interface.

This sequence ensures secure, multi-layered validation, protecting against unauthorized access and ensuring the integrity of user authentication data. The diagram highlights the collaboration between the user interface, SGX-BioShield, Key Management Service, Secure Storage, and Device Manager to achieve secure authentication.

3.4 **Proposed architecture** SGX-BioShield

The proposed architecture, SGX-BioShield, is an advanced implementation designed to enhance the security of the MOSIP Authentication Service by leveraging Intel SGX enclaves for secure biometric decryption and matching. By isolating sensitive operations within a hardware-based secure environment, this design ensures the confidentiality, integrity, and robustness of user authentication processes. The architecture addresses critical security concerns, particularly in scenarios where sensitive identity data and cryptographic keys need to be protected from

unauthorized access. The system is divided into three distinct zones: the Request Zone, the External Services Zone, and the Secure SGX-BioShield Zone, each with defined roles and responsibilities to ensure a seamless and secure workflow.

The Request Zone acts as the entry point for all authentication requests. It accommodates both users and third-party service providers, serving as an interface between external entities and the secure internal system. At the heart of this zone is the API Interface, which validates and processes authentication requests. This component securely transmits encrypted biometric data and related request parameters to the External Services Zone over a secure communication channel, safeguarding the data from unauthorized interception or manipulation during transit. The API Interface plays a vital role in ensuring the security and reliability of the request-handling mechanism, providing a robust foundation for the authentication process.

The External Services Zone manages sensitive data storage and key handling, leveraging two critical components: the Key Management Service (KMS) and the ID Repository Service. The KMS ensures the secure management of encryption keys using a Hardware Security Module (HSM) and a dedicated key storage mechanism. By securely retrieving and transmitting keys to the Secure SGX-BioShield Zone, the KMS ensures that encryption keys remain inaccessible to unauthorized entities throughout the authentication workflow [60]. Simultaneously, the ID Repository Service stores encrypted biometric and demographic data in distinct databases, ensuring data confidentiality and integrity. Upon request, the repository transmits encrypted biometric data to the Secure SGX-BioShield Zone for further processing. This division of responsibilities ensures that sensitive data remains protected, even in the event of a system breach. At the core of the architecture lies the Secure SGX-BioShield Zone, which is responsible for all critical operations, including decryption and biometric matching. This zone is built around Intel SGX enclaves, which provide hardware-based isolation, ensuring that sensitive computations are shielded from external threats [83].

The workflow within this zone begins with the Key Decryption Module, which retrieves encrypted keys from the KMS and decrypts them securely within the enclave. This isolation ensures that the decryption keys remain inaccessible outside the enclave, safeguarding them from unauthorized

access or memory snooping. Following this, the Biometrics Decryption Module utilizes the decrypted key to process encrypted biometric data received from the ID Repository Service, extracting usable biometric information within the enclave.

The decrypted biometric data is then handed over to the Biometric Operations Interface (BOI) SDK, which performs a 1:1 biometric matching to verify the user's identity. This matching process is conducted entirely within the enclave, guaranteeing the integrity and confidentiality of the authentication process. Upon successful matching, the Authenticated Response Module generates a cryptographically signed authentication response. This signature, generated within the enclave, ensures that the response is tamper-proof and authentic, thereby reinforcing trust in the authentication results [60].

The final step in the process is carried out by the Verification Response Module, which validates the cryptographic signature of the response generated by the enclave. By verifying the signature, this module ensures that the response has not been tampered with during transmission. Based on the validation outcome, the Verification Response Module provides a definitive "Yes" or "No" result to the requester, confirming whether the authentication was successful.

The data flow in SGX-BioShield begins with an authentication request from the Request Zone. The API Interface transmits this request to the External Services Zone, where the KMS and ID Repository Service provide the necessary encrypted keys and biometric data, respectively. These encrypted components are securely processed within the Secure SGX-BioShield Zone, where decryption and biometric matching occur entirely inside the SGX enclave. Following successful authentication, the system generates a signed authentication response, which is validated before being sent back to the requester. This workflow ensures end-to-end security, minimizing the risk of unauthorized access at every stage [60].

The SGX-BioShield architecture incorporates several critical security features to enhance the overall integrity and robustness of the system. The use of Intel SGX enclaves ensures that sensitive computations are isolated within a secure hardware environment, protecting against both hardware- and software-based attacks [83]. All data remains encrypted during transmission, and

decryption is only performed within the enclave, ensuring confidentiality at all times. The use of cryptographic signatures further enhances the authenticity of the responses, making them tamper-proof and reliable [83]. By separating data storage and processing responsibilities, the architecture minimizes the system's attack surface, reducing potential vulnerabilities.

This modular and scalable design makes SGX-BioShield well-suited for a wide range of high-security applications, including national ID verification, financial authentication, and secure healthcare access. By integrating hardware-based isolation, encrypted communication, and robust signature mechanisms, the architecture provides a reliable and scalable solution for identity authentication in sensitive and demanding environments [83][60].

3.5 Advanced Hybrid IDMS Architecture Leveraging Intel SGX

This architecture showcases a robust approach to biometric data protection, leveraging Intel SGX technology to establish a secure and trusted environment. The integration with ABIS provides reliable and efficient biometric deduplication and identification, crucial for maintaining the integrity of identity management systems like MOSIP.

This study acknowledges the benefits of centralized systems and incorporates these with various other approaches to develop a hybrid architecture. The resulting design enhances scalability, availability, resilience, and, most importantly, security and performance. This is especially significant in the context of 1 (one-to-many) matching and deduplication where biometric data from an enrollment request must be compared against the entire dataset of stored biometrics a process that typically introduces latency and performance challenges.

This proposed architecture combines centralized, decentralized, and federated approaches integrated for enhance scalability and security in addition to the main objective of improving the performance particularly in the case of 1 Matching (1:N matching), for Ethiopia National ID system. The system integrates several advanced technologies including blockchain, IPFS, and fog computing, to decentralize the biometric data and key aspects of the identity management process while ensuring robust protection of biometric data and efficient user authentication. The Blockchain and **IPFS** ensure the secure, distributed storage of user identity data, while fog

computing brings computing resources closer to the user, improving response times and reducing the load on central cloud servers.

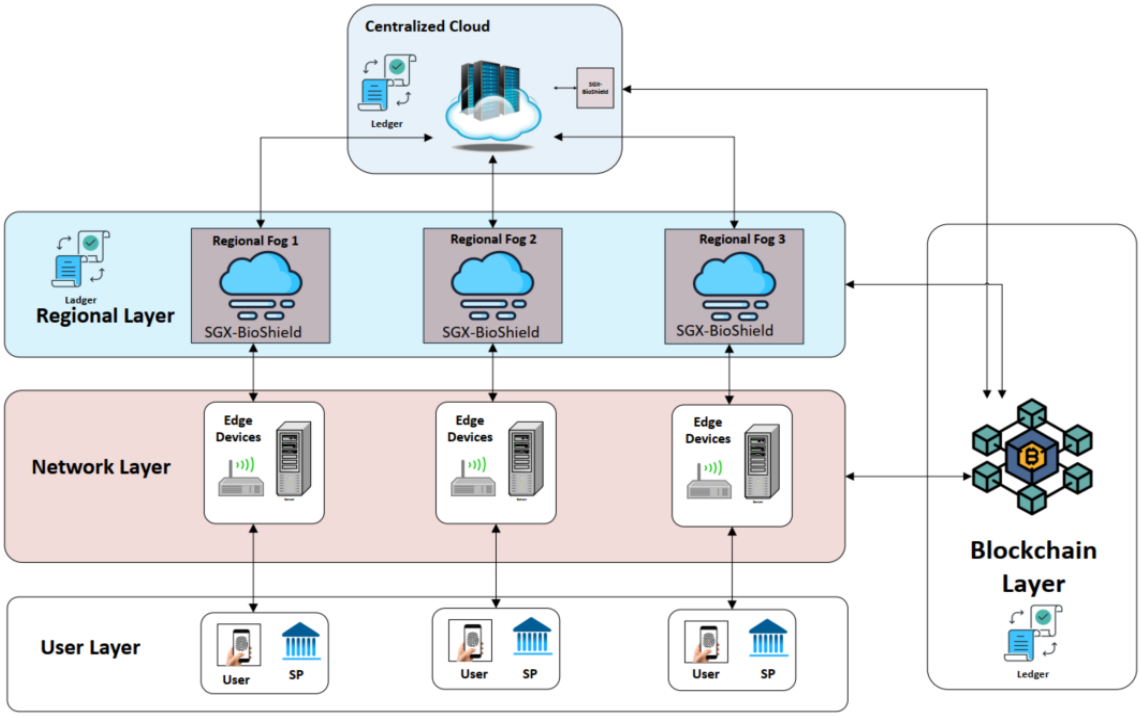

Figure 10. Advanced Hybrid IDMS Architecture Leveraging Intel SGX

DIM is the supporting pillar for all online services and the foundation for security and authentica tion mechanisms. Due to high level of heterogeneity, scale, and configuration complexity of such environments, enabling trustworthy DIM is crucial and seriously challenging [61]. The integration of advanced technologies like biometrics, blockchain, and fog computing offers a potential solution by creating a scalable, distributed system capable of meeting the needs of a large, decentralized population [1].

3.5.1 Description and Workflow of Layers

The proposed hybrid identity management architecture integrates secure, scalable, and decentralized elements to enhance data protection, performance, and user control. This architecture is organized into several layers, each with specific roles and responsibilities.

The User Layer includes users and service providers (SPs) who interact with the system. Users, whether residents or third-party entities, access the system through biometric devices or other user interfaces, while service providers use these interfaces to initiate or perform authentication

processes. Users submit biometric data through a secure interface, and service providers forward these authentication or access requests to the next layer.

The Network Layer consists of edge devices that manage communication and data processing at the network's edge, ensuring low latency and efficient resource utilization. These devices handle incoming biometric and service requests from the User Layer and forward them to the Regional Fog Layer. At this stage, edge devices may preprocess or secure the data before passing it on for further authentication or data handling.

The Regional Layer comprises Regional Fog Nodes, which implement SGX-BioShield instances that leverage Intel SGX technology to provide a secure environment for processing sensitive data, such as biometric information. Within SGX enclaves, biometric data is decrypted and securely processed, isolated from potential system vulnerabilities. The Regional Fog Nodes handle encrypted data from the Network Layer, perform necessary biometric matching, and communicate with the Cloud Layer for verification and further data processing.

The Cloud Layer serves as the centralized point for data and service management and includes components such as a centralized cloud server and a Key Management Service (KMS). The cloud server manages data storage and services, while the KMS securely handles encryption keys to ensure that only trusted nodes can access critical resources. The Central Cloud Server and KMS coordinate data encryption and decryption processes, providing secure key management for SGX enclaves. Once processed, authentication results are sent back through the layers to the User Layer.

The Blockchain Layer consists of distributed nodes that maintain data integrity, auditability, and transparency through a distributed ledger. This layer logs authentication attempts, transactions, and other critical events. These events are recorded on the blockchain to ensure a tamper-evident history, and nodes in different regions provide data replication and consensus to support this functionality.

The Security Layer oversees encrypted paths and security policies across all components, safeguarding data in transit and at rest. This layer ensures that all communication between layers and devices is encrypted using secure protocols, such as TLS, and enforces strict access control and monitoring mechanisms to further protect the system.

To strengthen security, several considerations are in place. Data Encryption is applied to all data, especially biometric data, ensuring it is encrypted both at rest and in transit. The KMS manages key generation and handling, securing data confidentiality and integrity. Sensitive operations are managed within SGX enclaves, which isolate them from the main operating system to prevent unauthorized access. Hardware-Based Security through Intel SGX ensures that decryption and biometric matching occur in a secure, tamper-resistant environment, with SGX attestation verifying enclave authenticity before granting access to critical resources. Secure Communication protocols, such as TLS, are used for data transmission between the User, Network, Regional Fog, and Cloud Layers, ensuring data integrity and confidentiality throughout the system. Access Control and Monitoring is enforced through role-based access control mechanisms and logging, which monitor access to critical components, such as the authentication server and KMS. Blockchain technology provides a transparent, tamper-proof log of events and access attempts, adding another layer of security.

The architecture utilizes several key technologies. Intel SGX is deployed in the Regional Fog Layer, creating secure enclaves for sensitive biometric operations and protecting data from hardware and software attacks. Blockchain Technology serves as a decentralized ledger for logging critical system events, enhancing data integrity and transparency. The Key Management Service (KMS) securely manages encryption keys, ensuring that only trusted entities can access or use these keys. Edge Computing enables data processing close to the data source, reducing latency and improving overall system efficiency. Finally, the Cloud Infrastructure provides scalable and centralized data management, with secure storage and processing capabilities.

Overall, this architecture is designed to securely handle sensitive data, particularly biometric information, at every layer, utilizing SGX for secure processing and blockchain for immutable logging. This multi-layered approach ensures a secure, efficient, and reliable identity management system that meets high standards for data protection and transparency.

3.5.2 Security and Performance Enhancements with SGX-BioShield

Leveraging **SGX-BioShield** in a hybrid architecture for identity management systems introduces robust security and performance enhancements. From a security perspective, SGX-BioShield

utilizes **Intel SGX enclaves** to create a trusted execution environment (TEE), where sensitive biometric data is securely processed. This setup ensures that operations like decryption, biometric matching, and data validation occur within protected enclaves, making them resistant to external tampering or attacks. By isolating these critical computations from the main operating system, SGX enclaves provide an additional layer of defense, preventing malware or intruders from accessing sensitive information. Additionally, the architecture upholds **data confidentiality** by keeping biometric data encrypted during transfer, with decryption occurring solely within the enclaves. Even in the case of a system breach, this ensures that sensitive data remains protected and inaccessible.

The tamper-resistant nature of SGX-BioShield safeguards against unauthorized manipulation, as any attempt to alter the enclave's code or data will render it non-functional. This is reinforced by remote attestation, which allows external systems to verify the enclave's integrity before sharing sensitive data, thereby establishing a strong chain of trust. This mechanism is particularly critical for identity management systems that demand high assurance of device and service authenticity. Furthermore, **SGX-BioShield** addresses the risk of insider threats effectively; administrators or internal personnel cannot access or modify data within the secure enclaves. Encrypted keys used for data protection are also managed securely within these enclaves, reducing the risk of key theft and enhancing the overall security framework.

From a performance standpoint, the **hybrid architecture** significantly boosts efficiency and responsiveness. By incorporating **edge and fog computing**, the system processes data closer to the source, reducing latency and delivering faster authentication and verification responses. This setup ensures that real-time operations do not overly rely on cloud services, optimizing the system's overall efficiency. Computationally intensive tasks, such as biometric matching, are delegated to regional fog nodes, which alleviates the load on the central cloud server and enhances the system's responsiveness. The architecture is also **scalable**, designed to handle an increasing number of users and devices seamlessly. By distributing tasks across edge devices, regional fog nodes, and the cloud, the system ensures that it can scale horizontally without performance degradation, which is essential for large-scale national identity systems.

Moreover, this design reduces network traffic by processing data locally and regionally, transmitting only necessary information to the cloud. This conservation of bandwidth is especially beneficial in areas with limited network infrastructure, ensuring consistent and reliable service delivery. The architecture also provides **high availability and reliability** through redundancy and fault tolerance mechanisms. If a regional node encounters an issue, data can still be processed through other nodes or the central cloud, ensuring continuous service. Load balancing further optimizes performance by distributing requests evenly across multiple nodes, preventing bottlenecks and enhancing system efficiency. Additionally, the architecture supports **data localization and compliance**, which is crucial for adhering to data protection laws that require local processing and storage of sensitive data. Overall, this hybrid approach balances security and performance, making it a powerful solution for secure and efficient identity management.

3.5.3 Benefits of the Architecture

Scalability and Load Distribution: By using regional fog nodes, the architecture reduces the computational load on the central cloud. This decentralized processing model enhances scalability, supports local data processing, and minimizes latency by reducing the distance data needs to travel.

Privacy and Security: The integration of SGX-BioShield in regional fog nodes and the centralized cloud ensures that sensitive identity data is processed in secure enclaves. The blockchain layer provides an immutable record of interactions, adding transparency without compromising sensitive information.

Improved Efficiency: By distributing processing tasks to the fog nodes and leveraging edge devices for initial data handling, the architecture reduces delays in the authentication process. This structure brings computing resources closer to the end user, resulting in more efficient identity verification. This hybrid architecture balances security, efficiency, and decentralization to support a robust and user-centric identity management system.

CHAPTER FOUR

4 Experiment and Analysis

4.1 Experiment

This experiment seeks to address the following research questions: What are the specific vulnerabilities associated with sensitive data processing in MOSIP? How to enhance the security on the identity management system? How to improve the performance of the identity management system? To address these questions, we plan to examine SGX by integrating it with the decryption and Matching process, which are parts of the MOSIP enrollment registration and Authentication Process. We will demonstrate the execution of a fingerprint decryption and matching Python application without SGX and then repeat the process with SGX integration, utilizing the enclaves. The results will be analyzed and compared to elaborate on the process.

To Describe the Environment for Performance Evaluation, Two environmental setups are used for performance tests. Gramine employed to utilize SGX in both environments, facilitating easy test on execution environment. The Gramine Shielded Containers (GSC) tool transforms a base Docker image into a new "graminized" image, which includes the Gramine Library OS and the Gramine-specific app configuration.

In this setup, we use Gramine to execute the application inside and outside an Intel SGX enclave. Modified python fingerprint application code used to be execute inside and outside SGX using and Gramine-SGX environments which represents Non-SGX and SGX-Bioshield deployments. The SGX-SDK, SGX drivers, and PSW (Platform Software) are installed in the SGX environment for Gramine to utilize SGX Enclaves.

5 Gramine Shielded Containers

Gramine Shielded Containers (GSC) provide a robust solution for securely running Docker containers within Intel SGX enclaves, making it ideal for cloud deployments where protecting sensitive data and code is critical. By integrating the Gramine Library OS, GSC allows applications

to run with minimal modifications while isolating both code and data in secure memory regions. The process begins with "graminizing" a Docker image through the gsc build command, which embeds Gramine OS, a manifest file listing trusted application files, and SGX-specific settings, thus preparing the container for secure enclave execution [77].

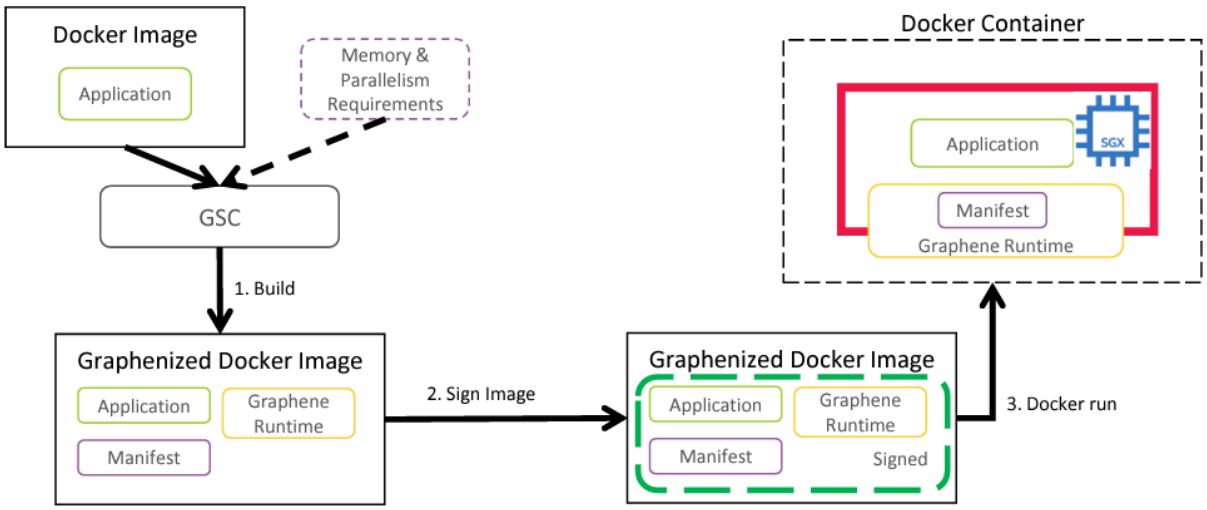

Figure 11. Gramine SGX mini Shielded OS Architecture

The graminized image undergoes a digital signing process using the gsc sign-image command. This step ensures the integrity and authenticity of the SGX configuration, making it ready for secure deployment. Once signed, the container can run in SGX mode, benefiting from hardware-based security protections. GSC also offers options for customizing builds, managing dependencies, and controlling container access through secure channels. This comprehensive approach makes GSC well-suited for organizations that need to execute sensitive workloads on shared infrastructure, relying on Intel SGX to maintain high levels of security [77] By October 2021, Graphene was renamed Gramine.

Gramine Shielded Containers: Docker containers are broadly used to deploy applications in the cloud. Using Gramine Shielded Containers (GSC) it offers the infrastructure to deploy Docker containers protected by Intel SGX enclaves using the Gramine Library OS [25]. The gsc tool transforms a Docker image into a new image (called gsc-<image-name>) which includes the Gramine Library OS, manifest files, Intel SGX related information, and performs the execution of the application inside an Intel SGX enclave via the Gramine Library OS [25]. It follows the

common Docker approach to first build an image and subsequently run a container of an image. At first a Docker image has to be graminized via the gsc build command. To execute the graminized image within an Intel SGX enclave, it must first be signed using the gsc sign-image command. After that, the image can be launched with the docker-run command. [25].

Data: A dataset from SOCOfing, consisting of PMB format images are used. The sample fingerprint templets encrypted and stored as a dataset, to simulate secure data storage. a similar fingerprint templets type are used to simulate an image received with an authentication request from the user of the third party SP. Both fingerprint templets are decrypted and the matching process`s executed inside and outside the enclaves.

Local Attestation Process between Enclaves: Local attestation enables one enclave to verify the integrity and authenticity of another enclave and the underlying hardware platform. The *sgx_sign* tool will sign the information exchanged between two enclaves. An enclave report contains measurements of the code and data in the enclave, a hash of the public key in the ISV certificate, user data, and other security-related information, all signed for verification by the platform that produced the report. In this test, there will be two Enclaves which are used to simulate attestation request Initiator and Attestation request verifier.

The **Initiator Enclave** generates a manifest containing the necessary information about the enclave and the application, sends a local attestation request to the Responder Enclave, and ensures secure communication before sharing sensitive data. The data is signed to ensure trustworthiness. The **Responder Enclave** completes the local attestation process, decrypts the data, and performs biometric processing. The response is signed for secure verification.

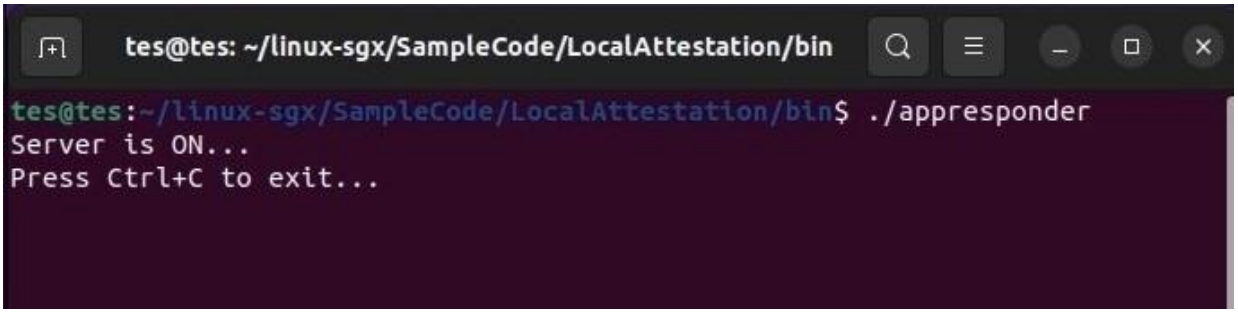

Figure 12. Starting the SGX Local Attestation Server: App Responder is running

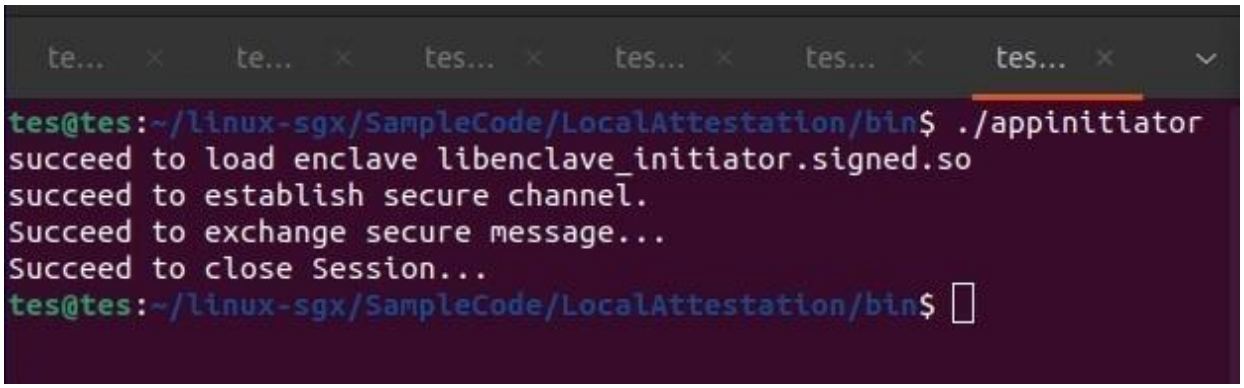

Figure 13. Local Attestation Server: Request Initiator request and successful attestation response

Metrics: Security and performance differences between execution inside SGX enclaves and traditional execution in the external environment are measured. Performance metrics are compared for both execution models to highlight overall security and performance outcomes.

Experiment 1: Non SGX, in this setup, the application runs in the operating system environment. Since no significant technology protects data during processing, data or code may be exposed. The performance expected to be better than an SGX environment.

Experiment 2: SGX-Bioshield , utilizes SGX features to execute operations inside enclaves. Two enclaves will be created, and local attestation will be performed for verification. The fingerprint matching application will be executed with enhanced security due to encryption mechanisms and access controls. However, the performance may be lower due to the overhead introduced by secure enclave operations.

5.1 Security Analysis

We have assessed how SGX enclaves secure data compared to traditional server environments, focusing on the additional protection gained from performing decryption and matching within SGX enclaves to prevent data leaks or tampering. We set up the environments to simulate the security differences between SGX-Bioshield and Non-SGX and SGX-Bioshield deployment. Our focus was on investigating the enclave security capabilities by using the features of SGX Enclaves, particularly how memory isolation and access restrictions differ between the two setups. A key aspect of SGX is that sensitive data in memory (such as the heap, stack, and code within the enclave) is protected from external access, even from privileged users or processes like debuggers.

In contrast, Non-SGX does not provide such isolation, making all memory accessible. SGX is also capable of protecting sensitive data even if the operating system is compromised, and the experiment was conducted to investigate the SGX capability to enhance the security of the sensitive data during processing.

Table 3. Security Test Result Comparison

Feature/Aspect	Non-SGX	SGX-Bioshield
Memory Dump Analysis	All memory accessible: Sensitive data can be exposed, raising security concerns.	Sensitive data inaccessible: Protects sensitive information in memory dumps, enhancing security.
Unauthorized Memory Access	Vulnerable: Sensitive data may be accessed using debugging tools.	Protected: Sensitive data remains inaccessible even under inspection attempts.
Memory Tampering	Susceptible: Memory can be modified, risking data integrity.	Protected: Memory tampering is blocked, ensuring data integrity and application security.
Attestation	Not applicable: Lacks mechanisms for verifying application integrity.	Supported: Built-in attestation features enhance trust and integrity verification.
Security Level	Moderate: Suitable for general applications but not for sensitive data.	High: Ideal for security-critical applications that require robust protection.
Use Case Suitability	General purpose: Suitable for less sensitive applications prioritizing performance.	Security-critical: Best for applications in finance, healthcare, or government sectors needing strong data protection.

Security Evaluation of SGX-Bioshield and Non-SGX

Based on the results from the tests conducted for both Non-SGX and SGX-Bioshield , we can summarize the findings and present a comparison table to highlight the differences in security and performance aspects between the two approaches. The security evaluation results for Non-SGX

setup indicated several findings. For the memory dump, a core file was created, but memory analysis indicated that all memory should be accessible. Warning messages were present about unexpected null characters in the command line, indicating potential issues with memory accessibility. In the unauthorized memory access test, the test completed successfully, but the output indicated that sensitive data may be accessible, showing a vulnerability in protecting data from unauthorized access. Furthermore, the memory tampering test was completed without any indication of protection against tampering, suggesting that the memory was susceptible to modifications.

In contrast, the results for SGX-Bioshield setup showed a more secure environment. A core file was created, but the analysis indicated that sensitive data should be inaccessible, suggesting effective protection of memory content. The unauthorized memory access test also completed successfully, and the output indicated that sensitive data within the enclave should be inaccessible, highlighting SGX's strong security measures. Additionally, the memory tampering test indicated that tampering should be blocked by SGX protection, demonstrating its ability to prevent unauthorized modifications to the enclave's memory. Lastly, the attestation test showed that local attestation is supported, with built-in attestation features enhancing trust and integrity verification.

Analysis: demonstrates a moderate level of security, making it suitable for general-purpose applications where data sensitivity is not a primary concern. However, the lack of effective memory protection mechanisms poses a risk, especially for applications handling sensitive information. SGX-Bioshield configuration provides a high-security environment suitable for applications that require strict confidentiality and integrity guarantees. The inability to access sensitive data through unauthorized means and the protection against memory tampering make it a better choice for security-critical applications.

5.2 Performance Analysis

- **Performance:** We analyze the performance of Non-SGX versus SGX-Bioshield setup for enclave execution, focusing on the overhead introduced the fingerprint decryption and **1:N matching** process to simulate the registration Process inside and outside SGX.

Table 4. Performance Comparison of SGX-Bioshield and Non-SGX Systems for 1:N Matching

Metric	SGX-Bioshield (Ratio)	Non-SGX (Ratio)	Comparison (SGX)
User Time	5.7	1	5.7 : 1
System Time	2.5	1	2.5 : 1
Total Elapsed Time	2.7	1	2.7 : 1
CPU Usage	1.6	1	1.6 : 1
Major Page Faults	0	1	0 : 1
Minor Page Faults	0.5	1	0.5 : 1
Involuntary Context Switches	0.25	1	0.25 : 1

5.3 Performance Analysis on Authentication

- **Performance:** We analyze the performance of Non-SGX versus SGX-Bioshield setup for enclave execution, focusing on the overhead introduced the fingerprint decryption and **1:1 matching** process to simulate the registration Process inside and outside SGX.

Table 5. Performance Comparison of SGX-Bioshield and Non-SGX Systems for 1:1 Matching

Metric	SGX-BioShield (1:1 Estimated Ratio)	Non-SGX (1:1 Estimated Ratio)	Comparison (SGX:Non-SGX)
User Time	1.4	1	1.4 : 1
System Time	1.2	1	1.2 : 1
Total Elapsed Time	1.3	1	1.3 : 1
CPU Usage	1.1	1	1.1 : 1

Major Page Faults	0	1	0 : 1
Minor Page Faults	0.2	1	0.2 : 1
Involuntary Context Switches	0.1	1	0.1 : 1

5.4 Results of Resource Utilization

This section compares the performance of Non-SGX and SGX-Base setup during the decryption of fingerprint data and the matching process. The key performance metrics observed in this experiment include CPU utilization, memory utilization, and network utilization.

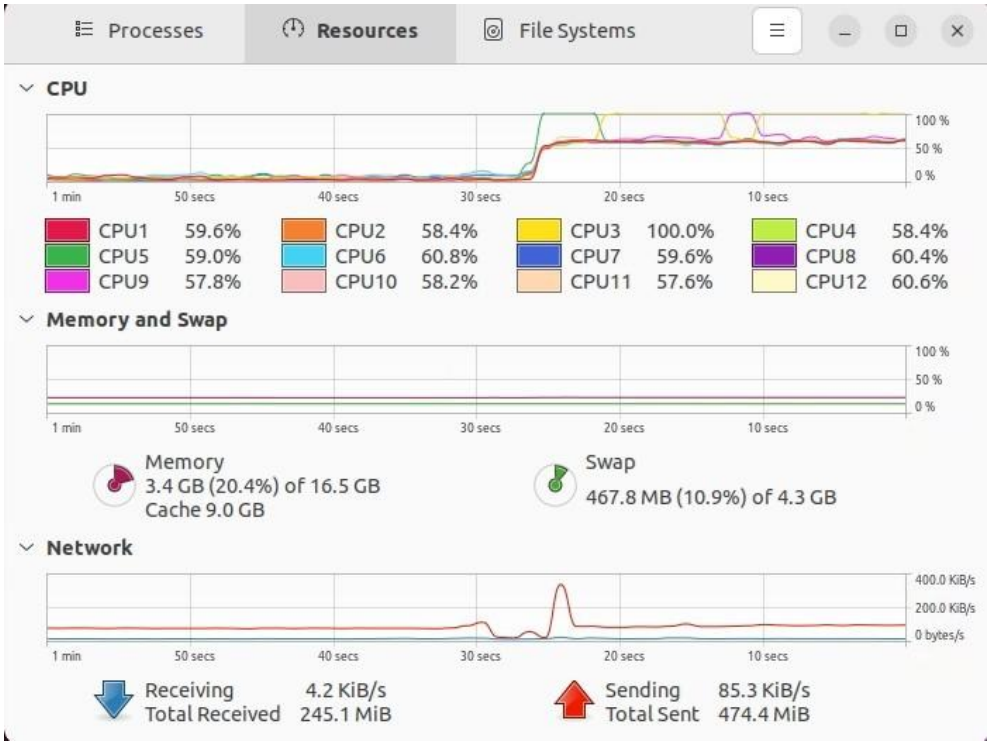

Figure 14. Non-SGX based setup resource utilization

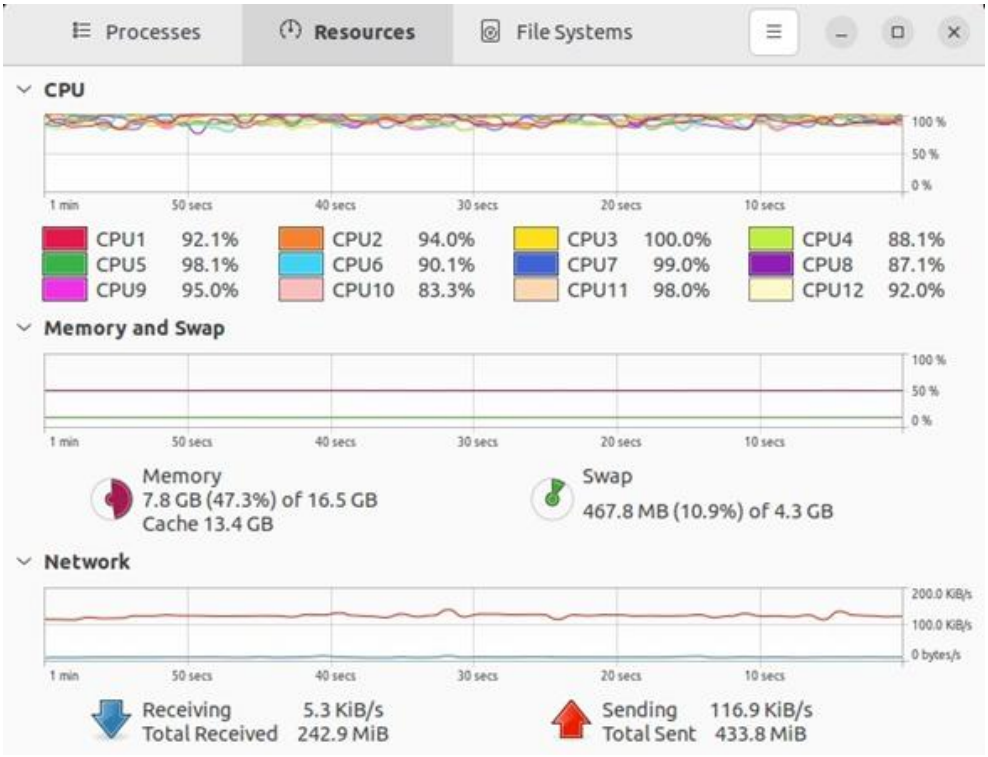

Figure 15. SGX-Bioshield Setup resource utilization

Non-SGX based setup: CPU utilization averaged 57% to 60%, with spikes reaching 100% on one core. Memory utilization reached 3.4 GB (20.4% of 16.5 GB total), with 467.8 MB of swap memory used. Network activity was minimal, with 4.2 KiB/s received and 85.3 KiB/s sent.

SGX-Bioshield setup; CPU utilization was higher and more consistent, averaging 87% to 100% across all cores. Memory utilization was significantly higher at 7.8 GB (47.3% of 16.5 GB total), while swap memory usage remained the same as GD. Network activity remained low, with 5.3 KiB/s received and 116.9 KiB/s sent.

Performance Comparison and Analysis: The experiment demonstrates that while SGX significantly enhances security, it introduces performance overhead due to secure enclave operations. CPU and memory utilization are higher in the SGX environment, reflecting the computational burden of running within a secure enclave.

Table 5. Resource utilization comparison

Metric	Non-SGX	SGX -based	Difference
CPU Utilization (Avg)	57% - 60% per core (with spikes up to 100%)	87% - 100% per core	Higher CPU usage in GS due to SGX enclave overhead.
Memory Utilization	3.4 GB (20.4% of 16.5 GB)	7.8 GB (47.3% of 16.5 GB)	GS consumes more memory due to enclave operations.
Swap Usage	467.8 MB (10.9% of 4.3 GB)	467.8 MB (10.9% of 4.3 GB)	No significant difference.
Network Received	4.2 KiB/s, Total: 245.1 MiB	5.3 KiB/s, Total: 242.9 MiB	Slightly higher in GS, but not a major factor.
Network Sent	85.3 KiB/s, Total: 474.4 MiB	116.9 KiB/s, Total: 433.8 MiB	Higher in GS, but still minimal impact.

This table compares system performance metrics between a non-SGX setup and an SGX-Bioshield setup, highlighting differences in CPU utilization, memory usage, swap usage, and network traffic. While SGX operations show higher CPU and memory usage due to SGX1's enclave overhead, the impact on network traffic and swap usage remains minimal. It's important to note that these limitations could be significantly reduced if SGX2 were applied in the experiment, offering better performance optimizations.

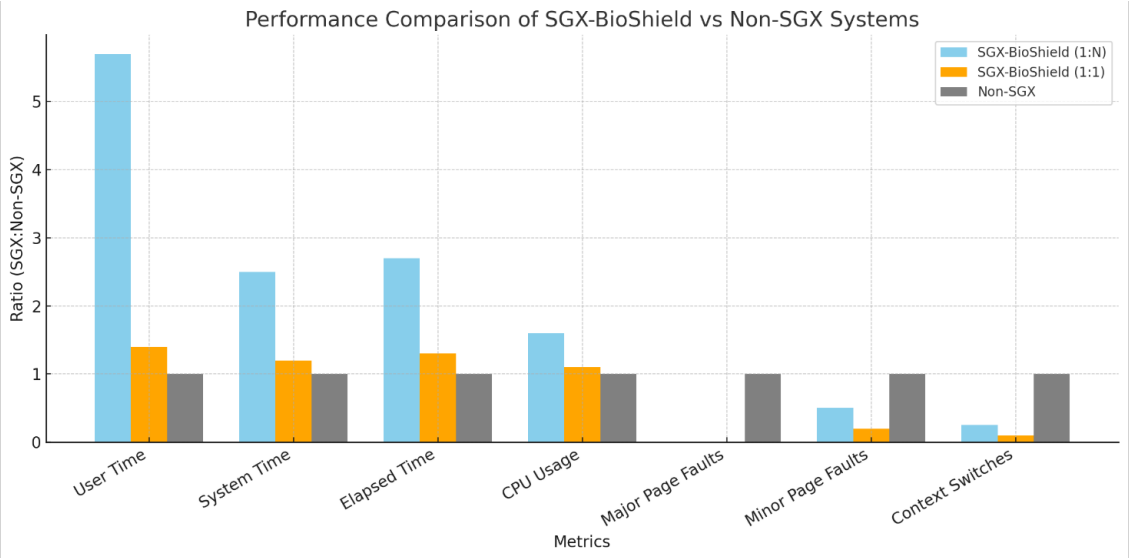

Figure 16. Graphical representation comparing the performance of SGX-BioShield versus Non-SGX systems for both 1:N and 1:1 matching processes

The performance comparison between SGX-BioShield and Non-SGX systems for both 1:N and 1:1 fingerprint matching reveals key insights into the efficiency of enclave-based execution. SGX-BioShield exhibits a higher overhead during the 1:N matching process compared to Non-SGX. However, this overhead significantly decreases during 1:1 matching, indicating that SGX performs well in simpler, smaller-scale operations. This is a positive sign for future improvements, especially with the planned transition to SGX2, which is expected to enhance performance further.

System time and total elapsed time are notably higher for 1:N matching, though they become more comparable in 1:1 matching, reflecting the ability of SGX-BioShield to handle authentication tasks with improved efficiency. Additionally, the comparison shows that SGX-BioShield introduces only a minimal increase in CPU usage during 1:1 matching, highlighting its ability to manage computational resources effectively for lighter workloads.

Furthermore, SGX-BioShield demonstrates better control over memory usage and scheduling, as reflected by fewer page faults and reduced context switching. This efficiency improves further during 1:1 matching, indicating strong potential for real-time operations. Overall, while SGX-BioShield introduces some overhead for complex processes, its performance during simpler tasks is promising, and future upgrades with SGX2 will likely reduce overhead, enhancing its suitability for both registration and authentication processes.

CHAPTER FIVE

6 Result and discussion

6.1 Result

The results clearly show that SGX-Bioshield setup is a more robust framework for running secure applications, especially those dealing with sensitive data. In contrast, Non-SGX setup may be more suitable for less sensitive applications but requires additional security measures to ensure data protection. As it provide High-Security Environment, Strict Confidentiality and Integrity Guarantees, Inability to Access Sensitive Data:, Protection Against Memory Tampering and it is Better Choice for Security-Critical Applications. Modern identity management systems improve identity verification, but challenges remain in data security, privacy, and attack mitigation. Technologies like SGX, ZKPs, and secure APIs are promising for enhancing the security of identity management systems [17] [29].

According to [75], minimizing the code executed in enclaves and implementing optimization techniques, can help mitigate performance overhead. For example, performance can be improved by 1.33× to 2.16×, as explained by [81]. in addition to that Programming for Performance, The security that is offered by the Intel® SGX architecture does not come for free in terms of impact of the performance on your application. Generally speaking Intel will seek to minimize the effect of the security checks and mechanisms that are required to support the security model offered by Intel SGX but some general awareness of where performance can be impacted will prove a useful tool to those seeking to get the best performance from their application. Developers that understand the potential overhead in the areas described in this section and apply the recommendations made here can successfully create applications that do not experience these addressable performance issues [76].

In conclusion, digital ID and identity management are evolving continuously, as seen in various nations that are progressively adopting ID systems to enhance their service delivery. However, it remains crucial to ensure these systems are secure, user-friendly, and promote inclusivity [18]. This research aims to delve into the challenges associated with identity management systems in

developing countries, with a particular focus on Ethiopia, which is currently implementing a national digital ID program [2] "Implementing a digital identity system has several benefits. To understand its critical components, processes, and required technologies that support a digital identity system, the key is to build an adaptable and flexible system that meets stakeholder needs [41].

6.1.1 Contributions to the Field

The main contribution of this research will be the idea of integrating SGX in to the identity management systems and preserve the security of sensitive data particularly during processing. This approach not only for MOSIP or for other identity management system, it will be significant contribution on the area of sensitive data security mostly in critical services or infrastructures. Data security on transit and at rest have positive attention from security experts and companies on the area. When it comes to data, security at use there is a lack of attention for this critical attack surface. Which can impose significant threat to the sensitive data. As this research focuses on data, security during process, the proposed SGX-integration solution has the potential to provide significant protection the field of cybersecurity.

6.1.2 Limitations

The most critical issue which has to be mentioned here, is the limitation of the SGX1, which is used for this experiment. Especially when it comes to draw the performance of the proposed SGX solution, the limitation of the SGX1 significantly magnified the performance overhead. This proposed solution would show significance amount of difference if SGX 2 is used.

6.2 Discussion

Based on our observation on the Experiment we would like to mansion areas of improvement and consideration for deployment. The first one is hardware selection of the SGX. Intel has two SGX types of Hardware features SGX1 and SGX2, based on the capabilities of the SGX 2, the most critical are using multiple Enclaves, enclave lifecycle management and dynamic memory allocation capability these features can make enamors improvement on the performance of SGX. Optimize the Manifest File: Minimizing file mounts by including only the necessary files and directories in the allowed files section of the manifest reduces the overhead during parsing.

Additionally, combining multiple related files into a single directory can minimize the number of mounts. Preload Libraries: Frequently used libraries can be preloaded using the LD_PRELOAD environment variable, which helps speed up startup by reducing the time spent loading shared libraries. It is also important to ensure that libraries are cached effectively in the system to reduce loading times. Keep the Enclave Alive: SGX enclaves are typically short-lived, but it can be beneficial to design the application to keep the enclave running for longer periods. Implementing a service to keep the enclave alive or using, a server model to handle multiple requests can reduce the overhead of re-initialization.

Reduce Initialization Overhead: If the application design allows, creating a single instance of the enclave to be reused for multiple operations reduces initialization overhead. Additionally, grouping similar operations together minimizes the number of times the enclave needs to be entered and exited. Use of Thread Pools: Implementing a thread pool allows handling multiple requests concurrently, keeping the enclave awake while managing several operations in parallel.

Profile and Optimize Code: Using profiling tools to identify bottlenecks in the code and focusing on optimizing sections that consume excessive time or resources can enhance performance. Service Management: If the application architecture permits, using a service manager such as system on Linux to start and manage the application as a service ensures that it remains active, allowing requests to be sent without restarting the service each time. By utilizing SGX2 and conducting these optimizations recommendations, significant performance enhancement can be achieved.

If SGX2 were used instead of SGX1, several potential improvements could address some of the limitations observed in your SGX1-based results, particularly around performance and memory management. SGX1's lack of dynamic memory allocation within enclaves forces developers to pre-allocate memory, leading to either memory underutilization or excess memory allocation. SGX2, however, introduces support for dynamic memory allocation through features like Enclave Dynamic Memory Management (EDMM), which allows enclaves to allocate memory on demand and resize as needed. This capability not only reduces memory overhead but also enhances efficient use of system resources [83], [84]. In practical terms, SGX2's dynamic memory

management could reduce the maximum resident set size and decrease page faults, thereby improving overall performance.

Another notable enhancement with SGX2 is the reduction in page faults. Since SGX1 lacks dynamic memory management, it experiences frequent page faults when accessing data beyond the pre-allocated enclave memory. SGX2, by allocating memory only as needed, reduces excessive page faults, which were very high in the SGX1 setup (over 7 million minor page faults observed) [85]. This capability is likely to decrease system time and elapsed time, contributing to faster overall execution. Additionally, SGX2 offers improved enclave lifecycle management by enabling enclave persistence, which allows enclaves to be reused across multiple operations without repeated initialization. This persistence reduces context switching overhead and minimizes the time spent entering and exiting enclaves [86], [86].

SGX2 also enhances multi-threading and supports better parallelism, making it more effective at handling multiple enclaves simultaneously. This improvement is beneficial for workloads that can be divided across multiple enclaves, as it enables efficient use of CPU resources and can reduce user time through better parallel processing [88]. SGX1's limitations in supporting parallelism and multi-enclave management make it less suitable for multi-threaded applications, while SGX2's enhanced support in these areas enables improved performance for such applications. Furthermore, SGX2 reduces the overhead associated with transitions between the secure enclave and the untrusted environment, optimizing these transitions by streamlining the security checks and context-switching processes required in SGX1 [89]. This reduction in transition overhead leads to lower system time and fewer involuntary context switches, improving the efficiency of operations that involve frequent enclave calls.

Memory-intensive applications also stand to benefit from SGX2's dynamic memory management. SGX1's static memory allocation can create bottlenecks in such applications, especially when memory requirements exceed the pre-allocated memory within the enclave. With SGX2, memory can be allocated as needed, enhancing memory handling and reducing memory pressure, which is critical for applications with fluctuating memory needs [90]. This improvement could lead to a decrease in the maximum resident set size and potentially reduce the elapsed time for memory-

intensive tasks, making SGX2 more suitable for complex applications with significant memory requirements.

In summary, if SGX2 were used instead of SGX1, you could expect reduced elapsed and system time due to optimized memory usage and fewer page faults. Dynamic memory management would likely lower the high minor page faults observed in SGX1. Persistent enclaves and enhanced lifecycle management would reduce context switching overhead, while improved support for multi-threading would allow for more efficient parallel processing. Lastly, the ability to allocate and free memory dynamically would optimize memory usage, making SGX2 a more performance-efficient and scalable option for processing sensitive data securely in enclaves [84], [86], [91].

CHAPTER SIX

7 Summary and future work

7.1 Summary

This thesis examines the integration of Intel Software Guard Extensions (SGX) into the Modular Open Source Identity Platform (MOSIP) to improve security and performance in identity management systems, with a particular focus on biometric authentication processes. We propose the SGX-Bioshield and Hybrid architecture as a solution to enhance the security of MOSIP, leveraging SGX's ability to protect sensitive data during processing. Furthermore, recognizing the limitations inherent in traditional, centralized identity management systems, we introduce a hybrid architecture that combines distributed Fog computing with a centralized cloud framework. This architecture also incorporates advanced technologies like Blockchain and IPFS to address scalability and performance challenges.

Through an extensive literature review, we identified key security gaps in conventional identity management systems, particularly concerning the handling of sensitive data. SGX technology, with its ability to create isolated secure environments (enclaves) for sensitive computations, emerged as a promising solution to address these concerns. Our SGX-Bioshield hybrid architecture leverages SGX's security features and combines them with the computational efficiency of Fog computing to bolster the technological capabilities of identity management systems. While this integration shows great promise, there is still limited research into the application of SGX in the context of identity management systems, despite its adoption by major cloud providers like Microsoft Azure and Alibaba Cloud [77], [131]. This gap presents an important avenue for future research.

Our experimental results demonstrate SGX-Bioshield's effectiveness in protecting sensitive data during processing. However, further exploration is needed to optimize its performance, particularly in terms of memory management and enclave lifecycle. These are areas where SGX2, the more advanced version of SGX, offers significant improvements over SGX1, which was used in our experiments. As outlined in the Discussion, SGX2 introduces several critical features such

as dynamic memory allocation, multi-enclave support, and improved enclave lifecycle management, which are essential for improving both the security and performance of the system.

In conclusion, this thesis presents a novel approach to enhancing the security and performance of identity management systems by integrating Intel SGX technology into MOSIP. The proposed SGX-Bioshield and Hybrid architecture effectively utilizes SGX's secure enclave capabilities to protect sensitive data during biometric authentication processes, while addressing the limitations of traditional centralized systems by incorporating distributed Fog computing. This hybrid architecture, combined with advanced technologies such as Blockchain and IPFS, holds significant potential to improve the scalability and efficiency of identity management systems. Although the integration of SGX into MOSIP has demonstrated promising results in securing data, there is room for further optimization, particularly in memory management and enclave lifecycle, areas where SGX2 provides notable improvements. As the field of SGX-Bioshield security in identity management systems is still emerging, this research highlights the need for continued exploration, especially in refining the performance and scalability of SGX technologies in real-world applications.

7.2 Future Work

Future research should focus on several key areas to further enhance the proposed SGX-Bioshield and Hybrid architecture. Firstly, testing SGX2 in the context of identity management systems should be prioritized, as SGX2 offers significant improvements over SGX1, particularly in terms of memory management, dynamic memory allocation, and enclave lifecycle management. These enhancements could lead to reduced performance overhead and more efficient resource utilization. Real-world implementation studies should also be conducted in collaboration with organizations deploying MOSIP, to gather empirical data on the practical effectiveness of SGX integration. This real-world feedback would be invaluable for refining and optimizing the system in future iterations. Additionally, further research should be conducted on alternative architectural improvements, particularly in transitioning from centralized systems to distributed Fog computing frameworks, as proposed in this thesis. Lastly, the integration of SGX with BigDL's Privacy-Preserving Machine Learning (PPML) software stack should be explored to secure the end-to-end big data and AI pipeline. These areas of research will contribute to the ongoing development of

secure, efficient, and scalable identity management solutions, which are essential for meeting the demands of an increasingly digital world.

CHAPTER SEVEN

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CHAPTER EIGHT

Appendices

API	Application Programming Interface
GD	Gramine-Direct
GDPR	General Data Protection Regulation
GS	Gramine-SGX
HSM	Hardware Security Module
KMS	Key Management Service
MOSIP	Modular Open Source Identity Platform
OTP	One-Time Password
SAML	Security Assertion Markup Language
SGX	Software Guard Extensions
SGX-SDK	SGX Software Development Kit
TLS	Transport Layer Security
UI	User Interface