iDSign: A Secure Lightweight NFC-Based Framework to Tap and Digitally Sign Documents

M.Tech Thesis

Submitted in partial fulfillment of
the requirements for the award of the degree
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submitted by

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under the guidance of
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May 2025

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CERTIFICATE

This is to certify that M.Tech Thesis entitled **iDSign: A Secure Lightweight NFC-Based Framework to Tap and Digitally Sign Documents** which is submitted by Himanshu Sharma, Roll No - 23/SWE/18, Department of Software Engineering, Delhi Technological University, Delhi in partial fulfilment of the requirement for the award of degree Master Of Technology (Software Engineering) is a record of the candidate work carried out by him under my supervision. To the best of my knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

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CANDIDATE'S DECLARATION

I Himanshu Sharma (23/SWE/18) hereby declare that the work which is being presented in the thesis entitled **iDSign: A Secure Lightweight NFC-Based Framework to Tap and Digitally Sign Documents** in partial fulfilment of the requirements for the award of the degree of Master Of Technology submitted in the Department of Software Engineering, Delhi Technological University is a bonafide record of my own work carried out during the period from August 2023 to June 2025 under the supervision of Dr. Divyashikha Sethia.

The material contained in the thesis has not been submitted by me for the award of any other degree of this or any other institute.

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Place: New Delhi

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This is to certify that the student has incorporated all the corrections suggested by the examiners in the thesis and the statement made by the candidate is correct to the best of our knowledge.

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Himanshu Sharma

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ABSTRACT

The growing dependence on digital systems for secure document exchanges requires efficient, lightweight digital signature solutions. Conventional methods, frequently dependent on Public Key Infrastructure (PKI) and cloud-based servers, introduce considerable challenges. PKI solutions suffer computational overhead, complex certificate administration, and security weaknesses, whereas cloud-based servers are susceptible to threats like data breaches, man-in-the-middle assaults, and unauthorized access. These risks are especially concerning in resource-limited and mobile environments.

Firstly, this work proposes iDSign, a novel secure and lightweight framework for digital document signatures that utilizes Identity-Based Cryptography (IBC) and a modified lightweight Identity-based Transport Layer Security (iTLS) protocol. iDSign mitigates extensive certificate exchanges and reliance on susceptible cloud infrastructures by improving efficiency with tamper-resistant Secure Elements (SEs). The framework is adaptable for various communication interfaces such as NFC, Bluetooth, and Transmission Control Protocol (TCP/IP), guaranteeing safe offline and proximity-based operations.

Secondly, this work also proposes the design and implementation of the iHDoc application based on the iDSign framework for the mobile-based signing of documents. iHDoc leverages NFC-based Host Card Emulation (HCE) for secure two-way communication and Bluetooth for effective post-authentication data transmission. NFC proximity reduces the risk of man-in-the-middle attacks and ensures the locality of reference. The mutual authentication component of the iDSign framework is compared with an Rivest–Shamir–Adleman (RSA)-based configuration to evaluate performance in real-world mobile scenarios. The results indicate that iHDoc based on iDSign significantly surpasses the RSA-based mutual authentication configuration in terms of execution speed, storage efficiency, and compatibility with mobile devices. This thesis rigorously examines iDSign's security attributes, covering its resistance to assaults and forward secrecy while quantitatively evaluating its communication and computing overhead. The results confirm iDSign as a lightweight, secure solution to digital document signing that is appropriate for offline, resource-limited, and mobile contexts.

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Chapter 1

Introduction

1.1 Overview

Having the option to safely and securely sign documents digitally has become crucial for various professions, including healthcare, finance, and legal services, in an increasingly digital environment. Digital signatures are essential as it replace physically signed paper documents, which can be easily lost or damaged [1]. By guaranteeing electronic transactions' integrity, authenticity, and non-repudiation, it provide legal validity to digital documents.

Digital signatures employ cryptographic techniques like hash functions and asymmetric encryption [4, 5]. Hash functions generate a unique fingerprint of the document. This fingerprint is digitally signed with the Signer's private key. The recipient verifies the hash, utilising the Signer's public key, and reconciles it against a fresh computation of the document hash. Both are the same, which guarantees document integrity and authenticity and Signer identity (non-repudiation). Apart from rendering paper-based signatures equivalent to the law, digital signatures provide additional benefits:

- *Efficiency:* Enables document processes, eliminating physical transit and storage requirements.
- *Security:* Enhances the integrity of sensitive data by reducing the risk of tampering and unauthorized access.
- *Efficiency in costs:* Saves on costs related to paper, printing, and manual processes.
- *Environmental Friendliness:* Reduces the reliance on paper, contributing to environmental campaigns.

Most operation environments increasingly test the reliability of digital signatures for use today. Resource-limited and mobile environments require cryptographic algorithms to be cost-efficient under limited computation capacity, storage, and connectivity. While secure in regulated environments, conventional Public Key Infrastructure (PKI)-based solutions face challenges in dynamic and decentralized scenarios. Consequently, the necessity for versatile, effective, and secure digital signature systems that facilitate proximity-based and offline functionalities is increasingly significant. The extensive utilization of smartphones and integrated secure features provides opportunities for lightweight cryptographic systems that function independently without ongoing server contact.

1.2 Motivation

Traditionally, digital signature implementations often involved physical tokens (like smart cards) or complex software installations, introducing barriers to adoption and ease of use. While providing numerous advantages, most existing solutions are web-based and susceptible to attacks [4,6,7]. Even though blockchains can also be used [8,9], both web and blockchain solutions require some external remote connection. These suffer from various challenges, such as:

- *Hardware and Software Dependence:* Many existing systems require specialist hardware devices (such as smart cards or USB tokens) or the implementation of related software applications. It creates complexity and potential compatibility difficulties and limits the mobility of signing across various devices and regions.
- *Security Vulnerabilities:* Digital signature systems can be subject to cyberattacks such as phishing attacks, malware, and man-in-the-middle attacks, which can compromise the secrecy of credentials and put signatures at risk [4,6,7].
- *Complex Authentication:* Verification of a Signer's identity with large certificates issued by centralized Certificate Authorities (CAs) for authentication purposes can increase complexity in terms of computational expenses, storage overheads and administrative complexity [10].

Recent improvements in proximity-based communication methods, like Near-Field Communication (NFC) with Host Card Emulation (HCE) [2] and Bluetooth, provide novel opportunities for in-person digital interactions independent of internet connectivity. However, secure mutual authentication over these mediums remains challenging due to transmission speed constraints and processing capabilities. Moreover, legacy systems often lack the mechanisms to guarantee security and usability in mobile-first scenarios. A unified framework integrating lightweight cryptographic operations with modern mobile communication interfaces is essential to meet evolving security and usability demands. The incentive is not cryptographic innovations on paper but to provide practical application through effective protocols that are both performance-oriented and attack vector-resistant.

1.3 Problem Statement

There are numerous problems with current digital signature solutions. Most current systems depend on specialist hardware devices or executing related software packages, producing complexity and lack of mobility. Further, current digital signature solutions are web-based and vulnerable to cyber attacks, breaking the privacy of credentials and exposing signatures to threat. Even, constructing a Signer's identity using large certificates for mutual authentication can incur computation costs, storage overheads, and management complexity.

Aside from the security and technical issues, digital signature systems nowadays are not scalable when used in varied environments, like public offices, hospitals, or government facilities. Such places normally demand dependable signing solutions that will function even if the internet connection is slow or broken. Web-based systems would depend heavily on the availability of constant internet and working servers, which may crash or

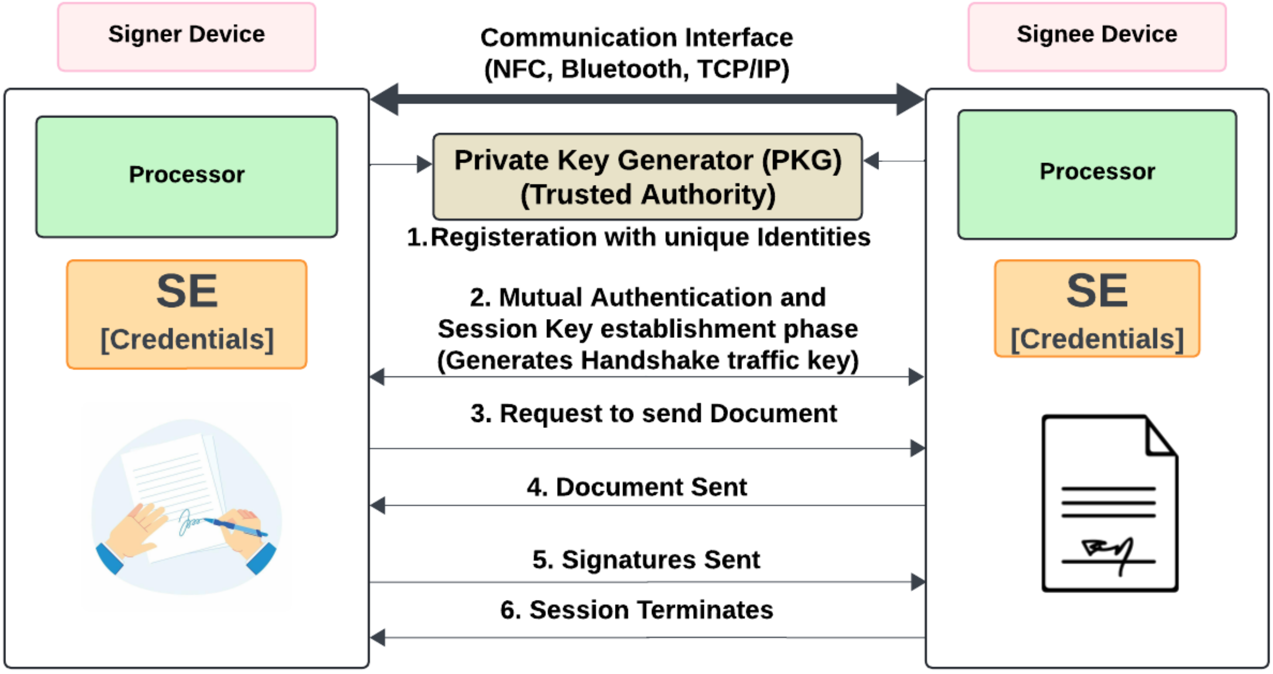

Signer Device
Communication Interface (NFC, Bluetooth, TCP/IP)
Signee Device
Processor
Private Key Generator (PKG) (Trusted Authority)
Processor
1.Registeration with unique Identities
SE [Credentials]
SE [Credentials]
2. Mutual Authentication and Session Key establishment phase (Generates Handshake traffic key)
3. Request to send Document
4. Document Sent
5. Signatures Sent
6. Session Terminates

Figure 1.1: iDSign framework block diagram

become unstable at the most inconvenient time. In addition, most conventional digital signature schemes are cumbersome to operate on contemporary mobile platforms using technologies such as HCE [2] or secure storage elements. These limitations indicate that a more scalable and secure architecture is necessary that can support simple digital signing in low-resource and high-mobility scenarios without compromising key security aspects or multistandard interoperability.

1.4 Proposed Solution

Therefore, there must be digital signature solutions prioritizing robust user authentication, confidentiality, easy cross-platform use, and physical tamper resistance. Design methodologies that rid complexity, simplify authentication, and have an easy-to-use interface are critical. The thesis presents a new iDSign framework overcoming these limitations with a light-weight and secure Identity-Based Cryptography (IBC) based framework [11] and a light-weight identity-based Transport Layer Security (iTLS) Protocol [10] for secure mutual authentication. Figure 1.1 depicts the flow diagram of iDSign. It does not rely on conventional PKI but incorporates IBC, thereby reducing the complexity of certificate management and ensuring robust security.

In order to ensure the applicability of iDSign in everyday mobile environments, this paper also introduces the design and implementation of a prototype application named iHDoc on a mobile-based platform, which combines low-energy NFC-based HCE [2] with the iDSign approach. NFC mobile phones are a perfect choice for face-to-face signing. NFC HCE mode enables a mobile phone to act as a smart card, avoiding extra hardware and being more flexible. iHDoc enables tap-based secure low-energy NFC communication for digital document signing over HCE on mobile devices, and Bluetooth is utilized for low-data-volume post-authentication data transfer. The suggested iDSign flexible solution is a robust one with the capability of significantly enhancing digital signing of documents in both in-person and remote environments.

1.5 Main Contributions of the Thesis

The key contributions of the thesis are listed below:

1. **Proposal of a novel iDSign (Identity-based Digital Document Signatures) Framework**

   a) Introduces *iDSign*, a secure and lightweight digital signature framework for resource-constrained and offline contexts, utilizing IBC [11] and the Hess Identity-Based Signature (Hess-IBS) scheme [12] to eliminate the need for certificate management.

   b) Detailed security and performance evaluation of iDSign through the iHDoc prototype.

   c) Comparative analysis of iDSign with existing digital signature solutions.

2. **Design and implementation of the Proposed iHDoc Mobile Application**

   a) Presents *iHDoc*, a proximity-based Android application based on iDSign, designed to implement and validate the iDSign framework using NFC HCE [2] and Bluetooth.

   b) Detailed performance evaluation of iHDoc mobile application.

1.6 Thesis Layout

The remaining thesis organization is as follows: Chapter 2 outlines the preliminaries. Chapter 3 contains an overview of related work. Chapter 4 presents the proposed iDSign framework. Chapter 5 presents the prototype implementation of the iDSign framework, iHDoc. Chapter 6 discusses the security analysis of the proposed protocol and the performance evaluation of both iDSign and iHDoc. In the end, Chapter 7 closes the work, summarizing key findings and outlining potential directions for further research.

Chapter 2

Technical Background

2.1 Near Field Communication (NFC)

Near Field Communication (NFC) is a short-range wireless technology that enables communication between electronic devices over a short distance (limited to less than 10 centimetres) and operates at a frequency 13.56 MHz. A simple wave or touch can establish a connection between two NFC-enabled devices. Based on radio-frequency identification (RFID), NFC enables seamless and secure data exchange between devices. NFC provides a versatile platform for numerous applications, including contactless payments, access control, data transfer, and device pairing.

The technology offers three primary modes of operation, as shown in Figure 2.1:

1. *Reader/Writer Mode:* An active NFC device (e.g., a smartphone) reads data from or writes data to passive NFC tags embedded in items. This mode enables information retrieval, product authentication, and marketing campaigns.

2. *Peer-to-Peer Mode:* Two NFC-enabled devices initiate direct communication and exchange data, such as contacts, photos, or small files, when in proximity. This mode facilitates quick and convenient data transfer without external infrastructure.

3. *Card Emulation Mode:* An NFC-enabled device emulates a contactless smart card, enabling it to interact with existing contactless card readers for applications like mobile payments [13] and access control [14].

NFC technology offers several advantages:

- *Simplicity:* NFC interactions are often initiated with a simple tap or touch.

- *Security:* NFC incorporates encryption and authentication mechanisms to protect sensitive data.

- *Versatility:* NFC supports many applications.

- *Low Power Consumption:* NFC is suitable for battery-powered devices.

- *Standardization :* NFC is standardized, ensuring device interoperability.

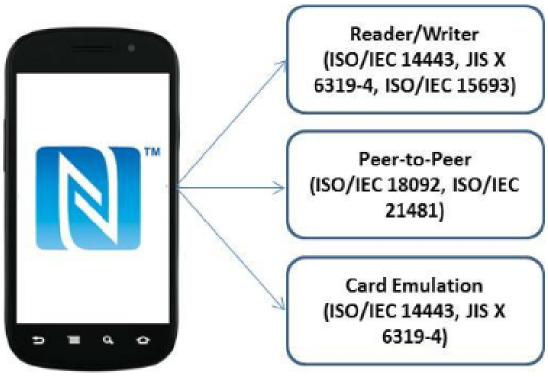

Reader/Writer
(ISO/IEC 14443, JIS X 6319-4, ISO/IEC 15693)
Peer-to-Peer
(ISO/IEC 18092, ISO/IEC 21481)
Card Emulation
(ISO/IEC 14443, JIS X 6319-4)

Figure 2.1: NFC operating modes [2]

2.2 Understanding NFC Host Card Emulation (HCE)

Contactless smart cards, such as those utilized for financial transactions or entry authorization, traditionally depend on embedded Secure Elements (SE) to securely store sensitive data and manage cryptographic processes, as shown in Figure 2.2. However, HCE substitutes the physical secure element with software-based emulation, allowing NFC-enabled devices to carry out transactions and interactions previously limited to physical cards. HCE is a technology that enables smartphones and other devices to act like real contactless smart cards [2]. HCE uses software to mimic smart card communication instead of specialized integrated hardware. HCE implements robust security mechanisms to safeguard confidential information when transmitted wirelessly. This technology is becoming increasingly common for mobile payments and other applications requiring tap-to-interact capability.

Application Protocol Data Units (APDUs) are the fundamental building blocks of communication in the HCE ecosystem [2]. These standardized packets of data, adhering to ISO/IEC 7816-4, are exchanged between the NFC reader and the HCE device. APDUs comprise a header, command data, and optional response data. The HCE service on the device receives command APDUs from the reader, processes the commands, and responds with appropriate response APDUs containing the requested information. HCE's robust security mechanisms ensure data confidentiality and integrity, making it a reliable solution for mobile devices to securely share signing information in the context of iHDoc mobile application, enabling quick and safe signing of documents with just a tap between devices.

2.2.1 ISO Standards for HCE APDU Commands

The ISO/IEC 7816 standard [15] governs the communication between NFC readers and HCE-enabled devices using APDUs. Developers originally designed this standard for physical smart cards but later extended it for HCE use cases. Below are key aspects of the ISO standards relevant to HCE communication:

- **ISO/IEC 7816-4: Organization, Security, and Commands for Interchange [15]**
  - This part of the standard defines the structure of APDUs, including command and response formats.
  - A command APDU typically consists of:

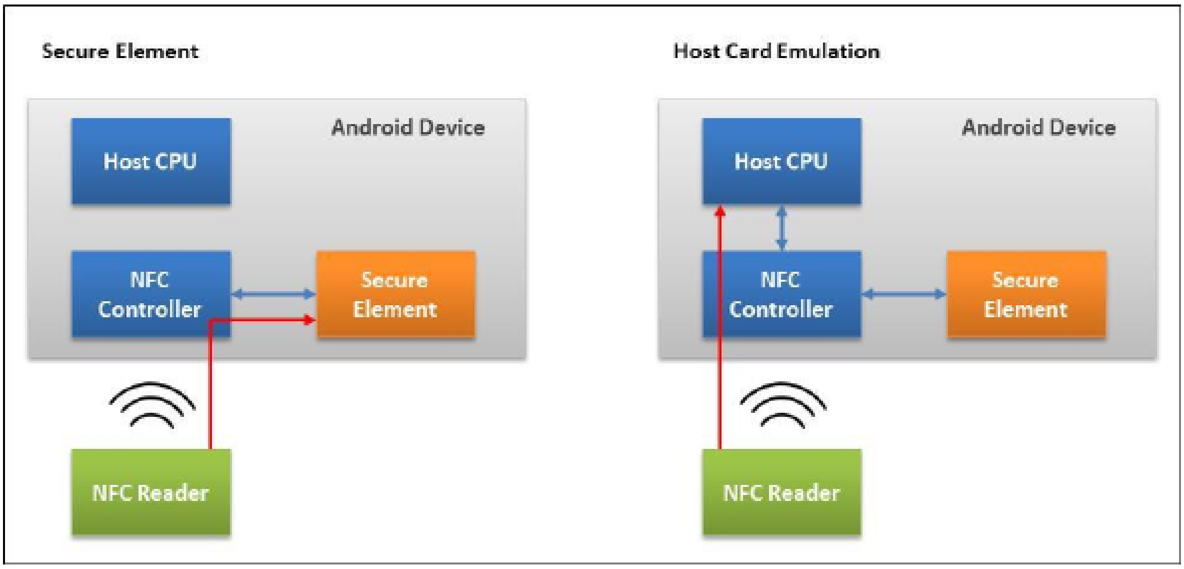


Figure 2.2: NFC communications with the SE (left) or with the host CPU using HCE (right) [2]

    - *CLA (Class Byte):* Identifies the type of command and security level.
    - *INS (Instruction Byte):* Specifies the operation to be performed (e.g., SELECT, READ, WRITE).
    - *P1, P2 (Parameter Bytes):* Provide additional parameters for the command.
    - *Lc (Length of Command Data):* Indicates the length of the data field (if present).
    - *Data Field:* Contains the actual data for the command (optional).
    - *Le (Length of Expected Response):* Specifies the maximum length of the response data expected from the HCE service.
  - A response APDU includes:
    - *Data Field:* Contains the response data (if applicable).
    - *SW1, SW2 (Status Bytes):* Indicate the processing status of the command (e.g., success, error codes).

- **ISO/IEC 7816-3: Electronic Signals and Transmission Protocols**
  - This part specifies the communication protocols between the NFC reader and the device, including the exchange of APDUs over NFC.
  - It ensures reliable data transmission, framing, and error detection mechanisms.
- **ISO/IEC 14443: Proximity Cards**
  - Defines the physical characteristics, radio frequency power and signal interface, and initialization protocols for proximity cards.
  - In HCE's case, this convention makes the NFC reader compatible with the emulated card functionality.

- **ISO/IEC 7816-8: Commands for Security Operations**
  - Offers instructions on how to use cryptographic operations like encryption and digital signatures, which are essential in secure HCE communication.
  - These operations guarantee data confidentiality, integrity, and authenticity in APDU transactions.

2.2.2 Architecture of HCE

The design of an HCE-enabled system will typically have three parts:

- *NFC Interaction*: It is the communication module. External NFC readers talk to the NFC-enabled device via this module. It deals with APDU transmission and reception, which are basic data packets standardized for use in communication.

- *HCE Module*: The HCE service is a software component running on the NFC device with the role of simulating the activity of a contactless smart card. It catches incoming APDUs from external NFC readers, interprets the commands, and reacts accordingly, simulating the activity of a physical smart card.

- *Secure Element Emulation Layer*: Some HCE implementations can involve a secure element emulation layer that emulates the behavior of a physical secure element [2]. The layer offers a trusted environment to store sensitive information, e.g., cryptographic keys and payment data, and perform secure operations, e.g., cryptographic processing and tamper-resistant storage. While the secure element emulation layer is not always needed, it does offer some extra security to HCE-enabled systems in cases where there is high-security demand.

- *Application Layer*: The application layer consists of user applications that use HCE functionality. Examples of these applications are mobile payment apps [13], access control systems [14], ticketing applications, loyalty apps, and others. All apps communicate with the HCE service to start transactions, exchange data with external NFC readers, and download secure resources stored on the device.

2.2.3 Operation of HCE

The HCE process is a sequence of steps [2] that takes place whenever an NFC device enters proximity with an external NFC reader:

- *Initialization*: As an NFC device enters the proximity of an external NFC reader, the HCE service will initialize and prepare itself to accept incoming communication.

- *APDU Exchange*: APDUs are exchanged from the external NFC reader to the HCE service, requesting actions or data. These APDUs often contain commands to start a transaction, authenticate the device, get data, or have some other operation.

- *APDU Processing*: When it receives an APDU, the HCE service executes the command according to the application logic and security regulations. It can include authentication of the request, decrypting the encrypted data, and access of secure resources, before performing the requested action.

- *Response Generation*: The HCE service, after executing the APDU, produces an appropriate response APDU with the requested information or indicator of the executed command. The system returns the response to the external NFC reader.
- *Transmission*: The response of the APDU is sent back to the external NFC reader that finishes the communication cycle. The external NFC reader can then respond and do as needed, be it to complete a payment transaction, provide access, or do some other action.

In HCE operation, the security system utilizes strong security controls to provide confidentiality, integrity, and authenticity of data being communicated between the NFC device and readers that are external. At different levels, encryption, authentication, and access controls, among others, are utilized to protect against unauthorized use, data interception, and tampering.

2.2.4 Advantages of HCE

HCE provides a number of benefits compared to traditional physical secure elements and other NFC-based solutions:

- *Cost-Efficiency*: Through the use of existing hardware and software capabilities, HCE avoids the use of specially created secure element chips, lowering NFC-enabled device production costs.
- *Enhanced Flexibility*: HCE facilitates dynamic provisioning and credential management, supporting easy integration with different applications and services without physical card limitation.
- *User Convenience*: The customers can just perform transactions and interactions using their devices that support NFC without needing to carry numerous physical cards or tokens.
- *Rapid Deployment*: Solutions based on HCE are readily deployable and even remotely updated through software updates, allowing for speedy distribution of new services and functionality without physical card replacement or modification of infrastructure.

2.3 Digital Signatures [1]

In the digital age, digital signatures have become crucial to document security. Digital Signatures act as a digital fingerprint, verifying a document's legitimacy and ensuring it remains unmodified since signing. Digital signatures leverage cryptographic techniques, including public and private keys, as shown in Figure 2.3. The Signer creates the digital signature using its private key to encrypt a distinct hash (a digest) of the document. Anyone can then decrypt the signature with the Signer's public key to confirm its authenticity by comparing the document's computed hash with the hash received by decrypting the signature. Digital signatures are necessary for building confidence and enabling safe transactions in many sectors where document integrity is crucial.

Digital Signatures provide essential security services, including authentication, data integrity, and non-repudiation. Authentication ensures that the claimed sender signed

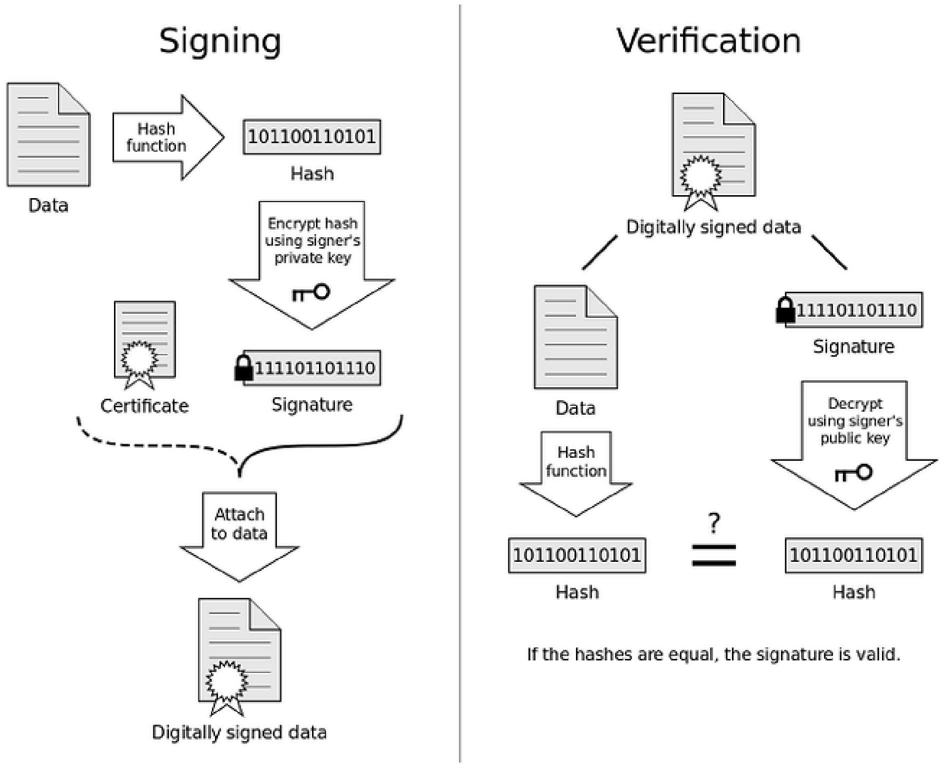


Figure 2.3: Digital signatures [3]

the message or document. Integrity ensures the system has not altered the content during transmission or storage. Non-repudiation ensures that the sender cannot deny having signed the message at a later stage. Several digital signature algorithms exist today, such as Rivest–Shamir–Adleman (RSA) [16], Elliptic Curve Digital Signature Algorithm (ECDSA), and more recently, identity-based schemes like the Hess IBS. Traditional methods like RSA depend on the PKI [16], which involves digital certificates and certificate authorities to validate the keys. However, such systems can introduce overhead, especially in mobile or resource-limited devices. Digital signatures are widely used in applications such as electronic contracts, software distribution, secure email, legal documents, and government records. Their growing importance reflects the need for secure, verifiable communication in a world increasingly dependent on digital interactions.

2.4 Transport Layer Security (TLS 1.3)

TLS is a basic cryptographic method that secures communications over computer networks [16]. It is a de facto implemented standard critical to internet surfing, emailing, and other web-based applications where data confidentiality and integrity are paramount. TLS establishes an encrypted channel of communication between two devices that send messages to each other, usually a client (e.g., web browser) and a server. It employs encryption for the protection of data in transit and authentication mechanisms to ascertain identity of the parties in communication. TLS 1.3, which is the latest version of the protocol, greatly boosts efficiency, security, and privacy by reducing the number of round trips required to create a secure connection [16]. It results in quicker page loading, reduced latency, and improved responsiveness for web applications. TLS 1.3 eliminates the insecure legacy, employs stronger contemporary ciphers, and encrypts a larger majority of the handshake process to deliver more extensive user privacy. Although TLS is extremely secure, it has the potential for high overhead since certificate sizes can be excessively large, which is difficult to accommodate in resource-poor devices.

Forward-secure cipher suites are the norm in TLS 1.3, eliminating legacy features like static RSA key exchange and SHA-1 hash functions. These improvements minimize the attack surface and enhance security for channel communication. TLS 1.3 streamlines the handshake by condensing it to a single round trip, optimized for utmost performance without compromising security. This makes TLS 1.3 quicker and more efficient to establish secure connections compared to previous protocol versions. But even TLS depends on PKI for the authentication of both parties. PKI mandates that certificates have to be signed by Certificate Authorities (CAs), and that adds latency because of the verification of certificates, especially when more than one certificate is used within the certificate chain. That is generating memory and computational cost, which is undesirable on low-resource systems like smartphones, IoT devices, or offline systems. These systems can find it difficult with the computational load of PKI, making TLS less desirable in applications where speed and simplicity and low resource utilization prevail the concern.

2.5 Identity Based Authenticated Key Agreement

Identity-Based Authenticated Key Agreement (IBAKE) is a cryptographic technique by which two users can build a common secret key securely only upon their own identity information. Adi Shamir first proposed the concept of IBC [11] with the entity's identity as its own public key in 1984 [17]. However, building an efficient and secure Identity-Based Encryption (IBE) scheme proved difficult until 2001 when Boneh and Franklin developed a novel scheme based on bilinear pairings on elliptic curves [17]. IBAKE enhances the agreement process since it does not involve the complexity of working with public key certificates. Rather, a reliable third party, the Private Key Generator (PKG), generates private keys for every user from their verified identity and eliminates the burden of a conventional PKI [18]. In the IBAKE protocol, identities are exchanged and independently calculated to derive the same shared secret key with the private key and the other's identity by both individuals. The shared secret key is used for secure communication and authentication.

IBAKE protocol streamlines mutual authentication through the elimination of certificate exchange. Rather than validating certificates generated by third-party authorities, the protocol enables each side to derive the shared session key from identity information and system-generated parameters. The protocol greatly minimizes communication and processing overhead in PKI-based key exchanges. At the core of this configuration is the PKG, which produces private keys using a master key that is secure and a map function to which the user identity is mapped to a point on an elliptic curve. The PKG should be secure and trustworthy since compromise would impact the overall system. When users receive their private keys, users can establish secure sessions without having to handle the PKG again, which is a welcome feature for offline or low-connectivity situations.

2.6 Bilinear Pairing

Bilinear Pairing is a strong cryptography idea [19]. It consists of three sets of prime order 'q' of mathematics: G1 and G2 as sets of addition, and G_{T} as a set of multiplication.

Bilinear Pairing involves one more special set of numbers, denoted as $\mathbb{Z}_q^*$, which contains all positive integers smaller than a large prime number 'q' excluding zero with the property of having a multiplication inverse modulo 'q'. The base of secure communication lies in a function called a pairing, defined as e: G1 x G2 -> G_T. This function requires two elements, each from G1 and G2, and maps the elements to an element in G_T. However, this mapping is not random - it possesses three key properties:

1. *Bilinearity:* Picture multiplying an element in G1 by a number 'a' and doing the same for an element in G2 by a number 'b'. The pairing of these multiplied parts is thus identical to the initial pairing raised to the power of the product 'ab'. The following eq. 2.1 captures this attribute:

$$(e(aP_1, bP_2) = e(P_1, P_2)^{ab}) \tag{2.1}$$

   Here, P1 and P2 are generators of their corresponding groups G1 and G2 respectively.

2. *Non-degeneracy:* There exist special non-trivial elements, P1 in G1 and P2 in G2, such that their pairing, e(P1, P2), is not the identity element in G_T (often denoted as 1 or 0 depending on the group). It ensures the pairing function is non-trivial, providing valuable information for cryptographic applications.

3. *Computable:* For all $S, T \in G, e(S, T)$ is easily computable.

   Assumption 1 [Bilinear Diffie-Hellman (BDH)]: For $x, y, z \in \mathbb{Z}_q^*$, given (P, xP, yP, zP), computing $e(P, P)^{xyz}$ is hard.

   Assumption 2 [Computational Diffie-Hellman (CDH)]: For $x, y \in \mathbb{Z}_q^*$, given (P, xP, yP), computing xyP is hard.

   Assumption 3 [Elliptic Curve Discrete Logarithm (ECDL)]: Given (P, xP), obtaining $x \in \mathbb{Z}_q^*$ is hard.

Bilinear pairings allow identity-based cryptographic protocols to perform digital signatures, encryption, and key agreement operations by enabling relationships between values that traditional discrete logarithm-based methods cannot achieve. The pairing operation creates a mathematical bridge between two elliptic curve groups and a target group, making verifying relationships in identity-based authentication and signature schemes possible.

2.7 Private Key Generator (PKG)

The PKG is the central part of any IBC system [17]. The PKG is a trusted authority that initializes the system parameters and generates user private keys from their identities. The function of the PKG is analogous to Certificate Authority (CA) in conventional PKI but without issuing or possessing digital certificates. In the setup process, the PKG chooses a master secret key and computes corresponding public system parameters. These parameters are something like an elliptic curve generator point, a bilinear pairing function, and secure cryptographic hash functions. After setting up the system, the PKG derives user private keys from its master secret key. It obtains each user's private key from the user's own identity, for example, email address or telephone number, first hashed into a curve point. The security of the entire identity-based scheme depends on the master key of the PKG not being revealed. When the master key is revealed, all derived private keys are insecure. Therefore, the PKG needs to be safeguarded with robust access controls, secure hardware, or in isolation inside a trusted execution environment.

2.8 Secure Elements

Secure Elements (SEs) [20] are security-hardened hardware components meant to safeguard sensitive information and carry out important cryptographic tasks in a highly secure setting. SEs find extensive use in mobile payments, identity authentication, access control, and digital signatures. They provide robust hardware security against attacks at the physical level and unauthorized access, making them compatible for safeguarding digital credentials and private keys. There are a number of different Secure Element types, such as embedded SEs, part of a device's chipset, Universal Integrated Circuit Cards (UICC) employed in SIM cards, and removable microSD cards. Each of these form factors complies with industry security requirements and provides cryptographic functions such as key generation, digital signatures, encryption, and secure storage.

2.9 Hess Identity-Based Signature (Hess-IBS) Scheme

The Hess IBS scheme [12] is an extremely efficient identity-based signature generation scheme, founded on the computation of calculating elliptic curve bilinear pairings. The scheme was first proposed by Florian Hess in 2002 [12]. Digital certificates are circumvented by employing a user's identity as the public key in this scheme. The security of the Hess-IBS scheme is based on intractability of the Bilinear Diffie-Hellman problem in pairing groups and follows the random oracle model. The system has four fundamental algorithms: Setup, Extract, Sign, and Verify. The trusted PKG produces system parameters and master keys in the Setup phase. In the Extract step, the PKG employs the hash representation of the user identity to retrieve the private signing key of the user. Signing consists of computing a pair of values from the identity and message hash through scalar multiplication and pairing operations. Verification is attained through the inspection of pairing relations and the validation of the integrity of the hash.

The scheme has two cyclic groups G and G_T of order of prime l and funtion of bilinear pairing $e : G \times G \to G_T$. Let P be a generator of G, and let H be a hash function that maps user identities to group elements in G. The PKG selects a random master key $t \in \mathbb{Z}_l^*$ and publishes $Q_{\mathrm{TA}} = tP$, keeping t private.

To extract a private key for a user with identity ID, the PKG computes $S_{ID} = t \cdot H(ID)$. To sign a message m, the signer chooses a random scalar k, selects an arbitrary $P_1 \in G$, computes $r = e(P_1, P)^k$, hashes (m, r) to get a scalar v, and finally calculates $u = vS_{ID} + kP_1$. The signature is the pair (u, v).

To verify the signature, the verifier computes $r' = e(u, P) \cdot e(H(ID), -Q_{\mathrm{TA}})^v$ and checks whether $v = h(m, r')$. If the condition holds, the signature is valid.

The scheme provides sound security guarantees, such as existential unforgeability in the presence of chosen-message attacks, assuming that the BDH problem is infeasible. Hess-IBS differs from other identity-based constructions in the best computational cost and signature size. The Signer only does one pairing exponentiation and one scalar multiplication. In the verification process, at most, two pairings and one exponentiation are needed, which can be reduced further if it accesses identities regularly.

Chapter 3

Proposed iDSign Framework

3.1 Introduction

In response to the growing needs for safe, efficient, and lightweight digital signature solutions, the iDSign system has been devised, a new system meant to break current limitations. iDSign is a multipurpose system that is designed to enable strong authentication, data protection, and secure document signing on resource-constrained environments, notably offline environments. The iDSign framework employs an iTLS protocol adaptation [10] for mutual authentication, a lightweight alternative to traditional certificate-based signing schemes. The signing process employs the Hess IBS scheme [12] for cryptographic protection with minimal computational overhead. The iHDoc, the proof-of-concept version of the iDSign framework, employs the low-power NFC HCE mode to enable tap-based in-site digital document signing. iHDoc analyzes the efficiency and practical use of the iDSign system within a real-world scenario in contrast to RSA-based mutual authentication [16]. Including a mobile application, iHDoc facilitates smooth signing and verification activities, facilitating offline and mobile use. The architecture, framework, and prototype design are presented in this section, emphasizing the innovation of iDSign and its ability to rectify the limitations of current digital signature systems.

3.2 Related Work

Chak et al. [5] presented AuthPaper, a method to increase the security and authenticity of paper documents. The process embeds an Authenticated 2D barcode within the document itself containing a digitally signed version of the document content and layout information. Utilizing the JavaScript Object Notation (JSON) data structure format and Quick Response (QR) codes for space-compressed visual encoding, AuthPaper enables effective storage and retrieval of critical document information. To achieve higher verification reliability, the authors adapted the open-source, popular barcode scanning library ZXing [21] into a modified version in order to incorporate extra algorithms to enhance QR code decoding precision even in poor conditions like poor-quality printing or a damaged barcode. AuthPaper's offline nature, independent of extrinsic databases or direct access to the network during verification, provides a complete and simple solution. But material barcode reliance also involves a vulnerability: if the barcode is compromised, it can become unreadable, which makes the authentication process questionable and unverifiable to the document's authenticity.

Gourab et al. 2017dsign introduced DSign, a novel digital signature system to make signing and verification more convenient using paperless business support. DSign uses a centralized database to maintain the critical metadata of a digitally signed document. Rather than including the whole content of the document within the signature, DSign uses the barcode or QR code as a reference to the database record of the document to minimize the computation load upon verification. This design circumvents the complexity of cryptographic processing on the client and facilitates quick verification of document origin. DSign also dispenses with the requirement for special hardware such as USB tokens in a manner that simplifies the signing and verification for users. However, utilization of a central database creates potential security risks, where integrity and confidentiality of the document details stored may be compromised by any unauthorized access, data breaches, or server crashes, thus affecting the trust value of the entire system.

Another new digital signature method using the utilization of biometric, such as fingerprints, for improved security and user authentication was introduced by Saxena et al. [22]. This thesis refers to the method as BioSign. Unique fingerprint characteristics are read by fingerprint scanners and encrypted into a "bio-cryptosystem." The system is combined with the document's hash, an exclusive digital fingerprint of document content, to generate an exclusive digital signature. The signature provides secure authentication of the Signer identity and document originator, since it is hard to replicate or forge. By correlating the biometric data with the signature, BioSign makes the process more secure than traditional digital signatures that depend entirely on cryptographic keys. Yet, biometric systems need to be perfect. They are susceptible to issues of accuracy such as false positives (misidentifying an unauthorized user) or false negatives (misfailing to identify an authorized user), which would lead to issues of security or privacy. Besides, biometric data capture and storage raise ethical concerns regarding the privacy of users and safeguarding of data since sensitive information can be misused in case it is hacked or accessed without users' authority.

Amer et al. [6] proposed a web-based approach to ensure the integrity and authenticity of PDF documents by preventing any unauthorized changes, which is referred to as PDFGuard in this paper. PDFGuard employs a secure cryptographic approach involving the use of the Secure Hash Algorithm 3 (SHA-3) along with the RSA digital signature scheme. SHA-3 generates an immutable and constant-length hash value (cryptographic fingerprint) of the document text, and a value of this kind is encrypted with the RSA algorithm and the sender's private key to generate a digital signature. The signature is appended securely to the PDF document, making it a tamper-evident stamp. Any alteration of the document would cause the recomputed hash and decrypted signature to vary, thus the proof of unauthorized alteration. The web-based character of PDFGuard provides convenient access and transparent integration into current document workflows, allowing users to verify the authenticity and integrity of PDF documents without special software installation. But as it is an internet-based solution, PDFGuard is vulnerable to some common cyber attacks such as man-in-the-middle (MITM) where the attacker can intercept and tamper with communication between the server and the user and phishing attacks where users are manipulated to provide credentials on forged websites. Moreover, PDFGuard's use of self-signed certificates, which do not carry the trust and confidence of their signed popular Certificate Authority (CAs) counterparts, might be inappropriate in high-security environments where stringent authentication and non-repudiation are of greatest concern. The lack of third-party trusted validation for the self-signed certificates

Table 3.1: Proposed iDSign framework: Comparison of existing digital signature schemes

Research	**Primary Method Used.**	**Imp.**	**Encrypt. Key Used**	**Signature Format**	**Verificat.**	**Limitations**
AuthPaper [5]	RSA, Qr Code	Soft.	Document Content + layout	2D barcode	Specialized Scanner, Offline	Physical damage vulnerability
DSign [4]	Centralized Signature Database	Web	Doc metadata (header, subject)	QR Code, Barcode (links to the database)	Web Access, Cloud Database lookup	Dependence on centralized database
BioSign [22]	Hashing biometric data, encryption	Soft.	Biometric Features	Biometric Hash	Fingerprint Scanner, hash checks	Accuracy issues in biometric authentication
PDFGuard [6]	RSA, SHA-3	Web	RSA algorithm	Hex String (Encrypted Hash)	Hash Comparison	Susceptible to web-based attacks
ECDoc [7]	ECDSA	Web	ECDSA algorithm	Encrypted Hash	Hash Comparison	Use of self-signed certificates

leaves room for potential certificate forging and impersonation attacks that compromise the system's overall security.

Rizqi et al. [7] investigated the application of the ECDSA in the protection of the integrity of PDFs. They contrasted their scheme, which has been termed ECDoc here, with other digital signature schemes like RSA and DSA and demonstrated how ECDSA was more secure, computationally efficient, and required less memory, particularly on resource-constrained platforms like the mobile phone. ECDSA is equally secure as RSA but using smaller key sizes and thus better placed to be used on devices with limited resources. The authors developed a web-based prototype which thoroughly exemplifies the feasibility of using ECDSA in PDF document signing and verification operations. The prototype illustrates how ECDSA can be used to reduce digital procedures and make PDF documents more secure. But, as with PDFGuard, the prototype's use of self-signed certificates is an impeding factor. Self-signed certificates do not have the trust and support of certificates drawn from trusted CAs but face improper issuance and misuse of certificates. This lack of trust can prevent the use of ECDoc in situations where it is absolutely necessary for the authenticity and non-repudiation of digital signatures due to the fact that the lack of independent verification would be undesirable in raising questions regarding the signatures' validity.

Existing solutions have limitations, including reliance on centralized databases, physical danger, cumbersome key management, and high security risk, shown in Table 3.1. Most importantly, none of the existing approaches achieves lightweight mutual authentication or employs SE for protecting credentials securely. Therefore, this paper proposes a new paradigm, iDSign (Identity-based Digital Document Signatures), which overcomes these crucial limitations using a secure, light-weight, and adaptive scheme for digitally signing documents.

3.3 Proposed iDSign Architecture

The iDSign (Identity-based Digital Document Signatures) framework enables secure and lightweight digital document signing across diverse devices and communication interfaces, with one device acting as a "Signer" and the other as a "Signee". They may communicate remotely over Transmission Conrol Protocol (TCP/IP) or via an NFC tap, providing flexibility in how they carry out the signing process. At the framework's core is the PKG; it can be imagined as a digital authority in an organization responsible for generating cryptographic keys based on the unique identities of each device registering with PKG. The secure storage and handling of the master secret key by the PKG is of utmost importance, as any compromise could allow unauthorized users to infiltrate the system and falsely register as signers or signees. It requires strong security to protect from such intrusions. After key generation, credentials are stored in secure SE that is tamper-proof on each device utilized for secure storage.

The mutual authentication between 'Signer' and 'Signee' is exchanged using a variant of the Lightweight iTLS protocol [10] such that both are verified to be authentic and does not permit unauthorized access. During this step, a session key is generated by the device such that future communication between the devices is encrypted. Hess IBS scheme is utilized for digital signatures since it is lightweight in nature [12] and therefore can be employed in resource-constrained devices. It uses the hash of the document according to the SHA-256 algorithm, extra variables, and the private key of the Signer to create a secure digital signature. Verification is done by recalculation of the hash of the document and use of some certain variables that are part of the Hess IBS scheme, along with the public key of the Signer, in order to compute the portion of the signature in order to compare it with the initial one.

3.3.1 PKG Security Strategies:

Although iDSign framework relies on the fact that PKG is safe and secure, one should realize that PKG security is of paramount concern in identity-based cryptographic schemes. A compromised PKG may produce spoofing keys or conduct man-in-the-middle (MiTM) attacks, which will undermine the system's overall security. Key Strategies for PKG security:

- *Hardware Security Modules (HSMs):* The PKG can leverage HSMs to securely store and manage cryptographic material within an isolated environment, thereby preventing unauthorized access [23].

- *Access Controls and Auditing:* Strict access controls restrict who can interact with the PKG, while ongoing auditing detects questionable activities, hence reducing the dangers of insider threats [24].

- *Secure Backup Mechanisms:* Encrypted backups of the PKG master key guarantee the key's availability in the event of hardware failures [23].

Table 3.2: Proposed iDSign framework: Symbols, abbreviations, and operators description

Notations	**Definitions**
PKG	Private Key Generator
P	Generator
e	Bilinear pairing
G	Additive Group of Prime order q
G_{T}	Multiplicative Group of Prime order q
s	Master Secret Key
P_{Pub}	Master Public Key
$H()$	Generic Hash Function
SPP	System Public Parameter
$M()$	Mapping Function: maps any string to a point on elliptic curve G
ID_{S}	Signer's Identity
ID_{D}	Signee's Identity
SK_{S}	Signer's Private Key
SK_{D}	Signee's Private Key
PK_{S}	Signer's Public Key
PK_{D}	Signee's Public Key
$\|\|$	Concatenation Operator
SignerHello	Contains parameters for Mutual Auth. relevant to Signer
SigneeHello	Contains parameters for Mutual Auth. relevant to Signee
EK_{S}	Ephemeral Public Key of Signer
EK_{D}	Ephemeral Public Key of Signee
x	Ephemeral Secret randomly chosen by Signer
y	Ephemeral Secret randomly chosen by Signee
N_{S}	Large Random Nonce chosen by Signer
N_{D}	Large Random Nonce chosen by Signee
HTK	Handshake Traffic Key
$HKDF$	HMAC-based Key Derivation Function
H_{DOC}	Hash of Document
SS_{S}	Signer's Shared Secret
SS_{D}	Signee's Shared Secret
EFM	Encrypted Finished Message
$E_{\mathrm{KEY}}()$	Data Encrypted by "Key"
$D_{\mathrm{KEY}}()$	Data Decrypted by "Key"
$ESign$	Encrypted Signatures via HTK : $E_{\mathrm{HTK}}(\mathrm{Sign})$

3.4 iDSign Framework Protocol

This work proposes a secure protocol for iDSign framework, which consists of three phases: *PKG Setup - Devices Registration*, *Mutual Authentication and Session Key Establishment Phase*, *Digital Signature Phase*. Table 3.2 contains a list of notations used in this work. The following assumptions are taken into account when creating the framework:

- This work assumes that the PKG is reliable, safe, and unaffected and will not conduct any aggressive attacks. Given that the master key that the PKG possesses is the source of all private keys.

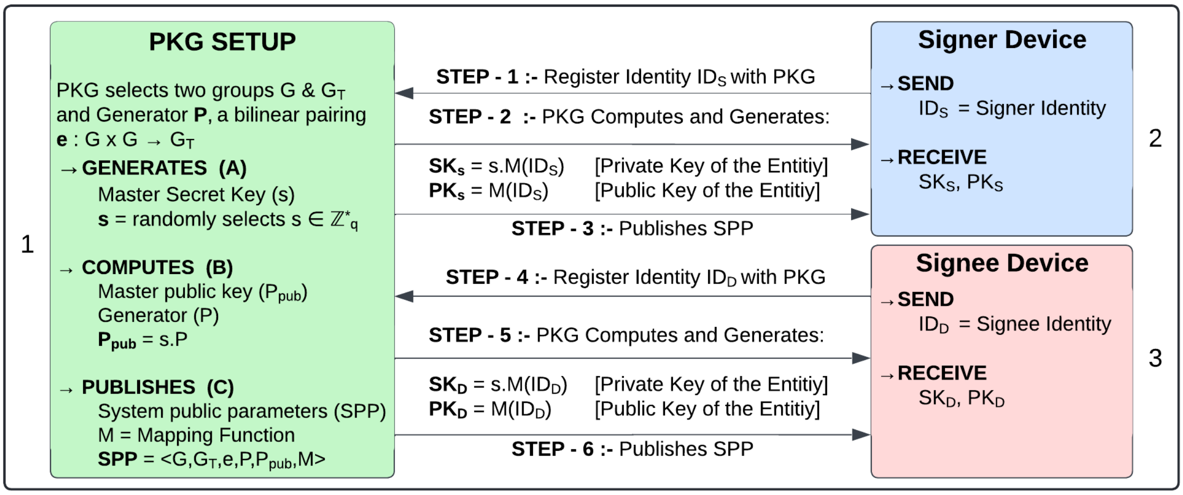

PKG SETUP
PKG selects two groups G & G_T and Generator P, a bilinear pairing e : G x G → G_T
→ GENERATES (A)
Master Secret Key (s)
s = randomly selects s ∈ ℤ*q
→ COMPUTES (B)
Master public key (P_pub)
Generator (P)
P_pub = s.P
→ PUBLISHES (C)
System public parameters (SPP)
M = Mapping Function
SPP = <G,G_T,e,P,P_pub,M>
1
STEP - 1 :- Register Identity ID_S with PKG
STEP - 2 :- PKG Computes and Generates:
SK_s = s.M(ID_S) [Private Key of the Entitiy]
PK_s = M(ID_S) [Public Key of the Entitiy]
STEP - 3 :- Publishes SPP
STEP - 4 :- Register Identity ID_D with PKG
STEP - 5 :- PKG Computes and Generates:
SK_D = s.M(ID_D) [Private Key of the Entitiy]
PK_D = M(ID_D) [Public Key of the Entitiy]
STEP - 6 :- Publishes SPP
Signer Device
→SEND
ID_S = Signer Identity
→RECEIVE
SK_S, PK_S
2
Signee Device
→SEND
ID_D = Signee Identity
→RECEIVE
SK_D, PK_D
3

Figure 3.1: Proposed iDSign architecture: PKG setup phase

- All cryptographic operations and key storage occur within a tamper-resistant SE.
- All the communication with PKG takes place over a secure channel.

The details of the phases are as follows:

3.4.1 PKG Setup Phase

Figure 3.1 illustrates how the Signer and Signee register with PKG and generate their Public and Private keys based on their identities.

- *Step 1:* The PKG picks elliptic curve groups G and G_{T}, a bilinear pairing $e : G \times G \rightarrow G_{\mathrm{T}}$, and a generator P of G forming the core of the pairing-based Identity-Based Key Agreement (IBAKA) mechanism utilized by iTLS for mutual authentication [10].
- *Step 2:* The PKG chooses a random value $s \in \mathbb{Z}_q^*$ as the master secret key. It safeguards this value, as it is essential for computing the private keys for the entities.
- *Step 3:* The PKG computes the master public key $P_{\mathrm{Pub}} = s \cdot P$, where P is the generator, makes it public to allow entities to verify the authenticity of messages from the PKG.
- *Step 4:* The PKG defines a Mapping function $M : \{0,1\}^* \rightarrow G$. This function maps an arbitrary string to a point on the elliptic curve group G and derives entity identities from unique identifiers.
- *Step 5:* The PKG provides the system public parameters $SPP = <G, G_{\mathrm{T}}, e, P, P_{\mathrm{Pub}}, M>$. These parameters are crucial for the framework's ability to work and enable entities to carry out cryptographic operations.
- *Step 6:* Entities enroll their identities with the PKG. An entity's identity (ID) is a unique identifier, such as a device ID or an email address.

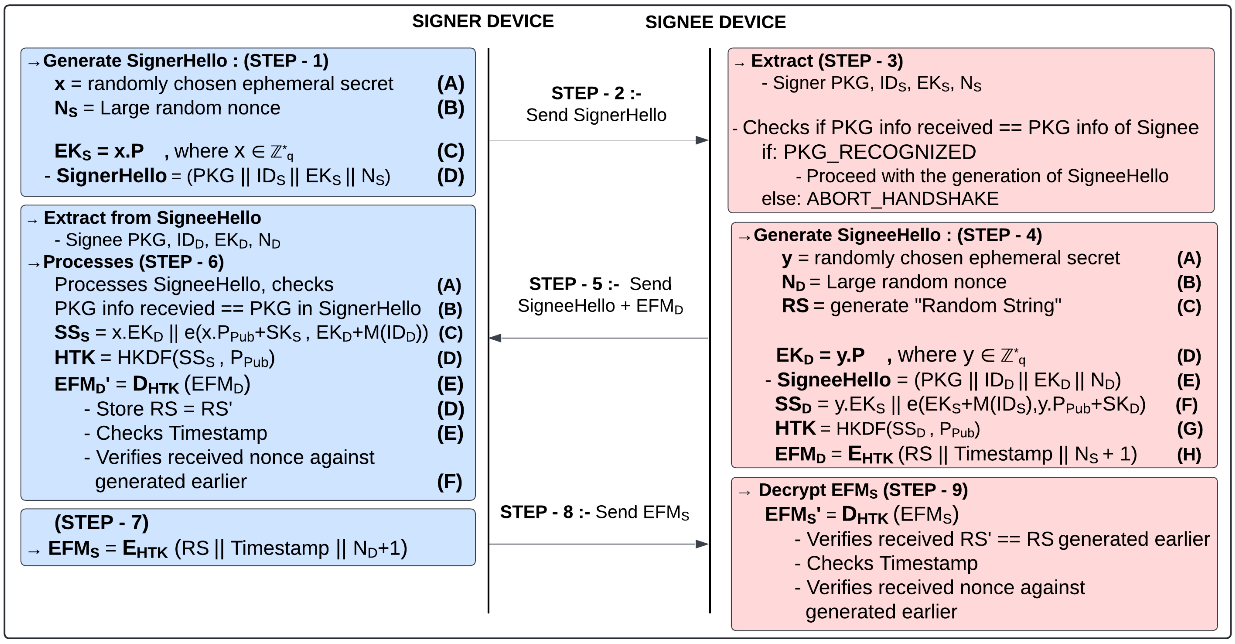

SIGNER DEVICE
SIGNEE DEVICE
→ Generate SignerHello : (STEP - 1)
x = randomly chosen ephemeral secret (A)
N_S = Large random nonce (B)
EK_S = x.P , where x ∈ ℤ*_q (C)
- SignerHello = (PKG || ID_S || EK_S || N_S) (D)
STEP - 2 :- Send SignerHello
→ Extract (STEP - 3)
- Signer PKG, ID_S, EK_S, N_S
- Checks if PKG info received == PKG info of Signee
if: PKG_RECOGNIZED
- Proceed with the generation of SigneeHello
else: ABORT_HANDSHAKE
→ Generate SigneeHello : (STEP - 4)
y = randomly chosen ephemeral secret (A)
N_D = Large random nonce (B)
RS = generate "Random String" (C)
EK_D = y.P , where y ∈ ℤ*_q (D)
- SigneeHello = (PKG || ID_D || EK_D || N_D) (E)
SS_D = y.EK_S || e(EK_S+M(ID_S),y.P_Pub+SK_D) (F)
HTK = HKDF(SS_D , P_Pub) (G)
EFM_D = E_HTK (RS || Timestamp || N_S + 1) (H)
STEP - 5 :- Send SigneeHello + EFM_D
→ Extract from SigneeHello
- Signee PKG, ID_D, EK_D, N_D
→ Processes (STEP - 6)
Processes SigneeHello, checks (A)
PKG info recevied == PKG in SignerHello (B)
SS_S = x.EK_D || e(x.P_Pub+SK_S , EK_D+M(ID_D)) (C)
HTK = HKDF(SS_S , P_Pub) (D)
EFM_D' = D_HTK (EFM_D) (E)
- Store RS = RS' (D)
- Checks Timestamp (E)
- Verifies received nonce against generated earlier (F)
(STEP - 7)
→ EFM_S = E_HTK (RS || Timestamp || N_D+1)
STEP - 8 :- Send EFM_S
→ Decrypt EFM_S (STEP - 9)
EFM_S' = D_HTK (EFM_S)
- Verifies received RS' == RS generated earlier
- Checks Timestamp
- Verifies received nonce against generated earlier

Figure 3.2: Proposed iDSign architecture: Mutual authentication phase

- *Step 7:* The PKG computes the private key $SK_{ID} = s \cdot M(ID)$ by mapping the Identity using the mapping function M and multipying it with the master secret key s.
- *Step 8:* The PKG securely sends the private key SK_{ID} to the respective entities. A mobile Trusted Platform Module (TPM) could establish this secure channel.
- *Step 9:* The associated public key $PK_{ID} = M(ID)$ is used by the entity. Anyone can use the publicly available hash function to compute the public key from the entity's Identity.

3.4.2 Mutual Authentication and Session Key Establishment Phase

Figure 3.2 illustrates the mutual authentication process between devices, leveraging a customized version of iTLS protocol [10], omitting traditional certificates in favour of streamlined ephemeral key exchanges and nonce-based verification. Both SignerHello and SigneeHello messages carry crucial elements such as the entity's unique identification, details about the PKG (which includes PKG's identifier, IBAKA algorithm used, and System Public Parameters), ephemeral public key and random nonce. This approach enables both parties to verify trust and independently compute the same shared secret key for secure communication.

- *Step 1:* Upon initiating the communication, Signer device generates SignerHello (containing the identifier of the PKG where the device is registered, Signer's Identity ID_S, Ephemeral Public Key EK_S and Large random nonce N_S). The Signer computes $EK_\mathrm{S} = x \cdot P$ where $x \in \mathbb{Z}_q^*$ is an ephemeral secret randomly chosen by the Signer device before sending a SignerHello message.
- *Step 2:* Signer initiates the mutual authentication by sending a SignerHello message.

- *Step 3:* Signee receives SignerHello and checks whether the PKG information presented is the same as that of the Signee device. Upon recognition, it generates SigneeHello; otherwise, the handshake terminates with an alert.

- *Step 4:* Upon successful validation, the signee device generates random string RS and SigneeHello (containing the identifier of the PKG where the device is registered, Signee's Identity ID_{D}, Ephemeral Public Key EK_{D} and large random nonce N_{D}). The Signee computes $EK_{\text{D}} = y \cdot P$ where $y \in \mathbb{Z}_q^*$ is an ephemeral secret randomly chosen by the Signee device. With the help of received EK_{S} and ID_{S} of Signer, Signee computes the shared secret $SS_{\text{D}} = y \cdot EK_{\text{S}} || e(EK_{\text{S}} + M(ID_{\text{S}}), y \cdot P_{\text{Pub}} + SK_{\text{D}})$ and the Handshake Traffic key (HTK) by extracting the shared secret through the Hashed Message authentication code (HMAC)-based key derivation function (HKDF) [25] $HTK = HKDF(SS_{\text{D}},\ P_{\text{Pub}})$. Upon successful calculation of HTK, the Signee device generates EFM_{D} by concatenating RS, current timestamp, and incremented nonce N_{S} and then encrypting with HTK, as shown in eq. 3.1.

$$EFM_{\text{D}} = E_{HTK}(RS||Timestamp||N_{\text{S}} + 1) \tag{3.1}$$

- *Step 5:* Signee responds with SigneeHello and EFM_{D}.

- *Step 6:* Upon receiving SigneeHello and EFM_{D}, Signer processes the same and checks if the PKG provided in SigneeHello matches up as that in the SignerHello. With the received ID_{D} and EK_{D} provided in the SigneeHello, Signer can also derive the shared secret $SS_{\text{S}} = x \cdot EK_{\text{D}} || e(x \cdot P_{\text{Pub}} + SK_{\text{S}}, EK_{\text{D}} + M(ID_{\text{D}}))$ and $HTK = HKDF(SS_{\text{S}},\ P_{\text{Pub}})$. Through derived HTK, the Signer decrypts $D_{HTK}(EFM_{\text{D}})$ and firstly stores the random string RS to use it later and then verifies the integrity and authenticity by checking the timestamp and nonce value against those generated earlier in the process by Signer.

- *Step 7:* After a successfully verification of timestamp and random nonce N_{S}, the signer device generates EFM_{S} by concatenating received RS from SigneeHello, current timestamp and incremented nonce N_{D} and then encrypting with HTK, as shown in eq. 3.2.

$$EFM_{\text{S}} = E_{HTK}(RS||Timestamp||N_{\text{D}} + 1) \tag{3.2}$$

- *Step 8:* Signer sends EFM_{S} to Signee device.

- *Step 9:* Signee device decrypts the received EFM_{S} and firstly verifies random string RS against previously generated, checks timestamp and nonce value against those generated earlier in the process by Signee. The authentication is marked as completed upon successful verification. Both devices use HTK to encrypt and secure further communication.

- Proof Of Both Devices Obtaining The Same Shared Secret:

By the bilinearity of the pairing [19], both the devices obtain the same shared secret. The shared secret SS_{S} computed on the Signer side is given by eq. 3.3:

$$SS_{\text{S}} = x.EK_{\text{D}} || e(x.P_{\text{Pub}} + SK_{\text{S}}, EK_{\text{D}} + M(ID_{\text{D}}) \tag{3.3}$$

Eq. 3.4 shows the substitution of identity-based elements:

$$= x.y.P||e(x.s.P + s.PK_{\text{S}}, y.P + PK_{\text{D}}) \tag{3.4}$$

Using pairing properties, eq. 3.5 distributes the pairing function over the sum of elements:

$$= x.y.P||e(x.s.P, y.P)e(x.s.P, PK_{\text{D}})e(s.PK_{\text{S}}, y.P)e(s.PK_{\text{S}}, PK_{\text{D}}) \tag{3.5}$$

Applying bilinearity further, eq. 3.6 expresses the pairings as exponentiated base pairings:

$$= x.y.P||e(P, P)^{x.s.y}e(P, PK_{\text{D}})^{x.s}e(PK_{\text{S}}, P)^{s.y}e(PK_{\text{S}}, PK_{\text{D}})^{s} \tag{3.6}$$

Eq. 3.7 presents the reordered expression computed from the Signee's perspective:

$$= y.x.P||e(x.P, y.s.P)e(x.P, s.PK_{\text{D}})e(PK_{\text{S}}, y.s.P)e(PK_{\text{S}}, s.PK_{\text{D}}) \tag{3.7}$$

Eq. 3.8 simplifies the structure using key definitions:

$$= y.EK_{\text{S}}||e(x.P + PK_{\text{S}}, y.s.P + s.PK_{\text{D}}) \tag{3.8}$$

Using the mapping of identities, eq. 3.9 rewrites the final pairing term:

$$= y.EK_{\text{S}}||e(EK_{\text{S}} + H(ID_{\text{S}}), y.P_{\text{Pub}} + SK_{\text{D}}) \tag{3.9}$$

Hence, both devices compute the same shared secret as shown in eq. 3.10:

$$SS_{\text{S}} = SS_{\text{D}} \tag{3.10}$$

3.4.3 Digital Signature phase

Figure 3.3 illustrates the Digital Signature process, leveraging the Hess IBS scheme [12]. The novelty in this phase resides in employing the Handshake Traffic Key (HTK), established during the mutual authentication phase, combined with an Identity-based Signature scheme for document signing. This strategy not only maintains the confidentiality and integrity of the delivered document but also enhances the overall security of the digital signature procedure. During the Mutual Authentication phase, both devices obtain the same HTK to secure further communication in the iDSign framework. In this phase, the Signee sends the document to the Signer, who then signs it using his identity-based private key via the Hess IBS scheme and sends it back to the Signee for it to integrate it with the document and can verify its authenticity using the Signer's public key.

- *Step 1:* Signer asks for basic document (Packet Number + Total Packets) information before receiving the actual document.
- *Step 2:* The Signee sends the requested document information along with the first packet. This process continues sequentially, and the Signer acknowledges each packet the Signee sends until all packets are received.

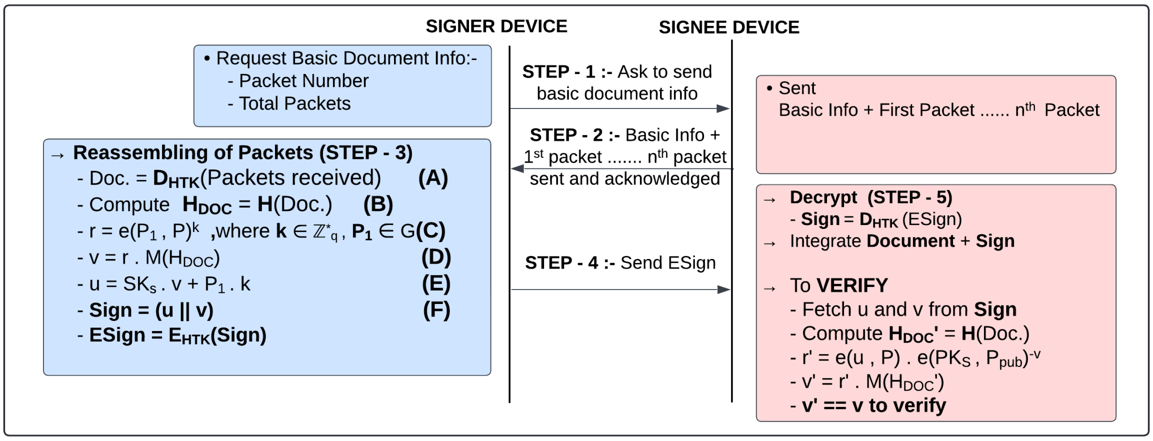

SIGNER DEVICE
SIGNEE DEVICE
• Request Basic Document Info:-
- Packet Number
- Total Packets
STEP - 1 :- Ask to send basic document info
• Sent
Basic Info + First Packet ...... nth Packet
STEP - 2 :- Basic Info + 1st packet .... nth packet sent and acknowledged
→ Reassembling of Packets (STEP - 3)
- Doc. = D_HTK(Packets received) (A)
- Compute H_DOC = H(Doc.) (B)
- r = e(P1 , P)^k ,where k ∈ ℤ*q , P1 ∈ G (C)
- v = r . M(H_DOC) (D)
- u = SK_S . v + P1 . k (E)
- Sign = (u || v) (F)
- ESign = E_HTK(Sign)
STEP - 4 :- Send ESign
→ Decrypt (STEP - 5)
- Sign = D_HTK (ESign)
→ Integrate Document + Sign
→ To VERIFY
- Fetch u and v from Sign
- Compute H_DOC' = H(Doc.)
- r' = e(u , P) . e(PK_S , P_pub)^-v
- v' = r' . M(H_DOC')
- v' == v to verify

Figure 3.3: Proposed iDSign architecture: Digital signature phase

- *Step 3:* The Signer decrypts the packets with HTK, reassembles them, computes the hash of the document extracted using SHA-256 method, denoted as $H_{\text{DOC}} = H(\text{Doc.})$. Using the Hess IBS scheme [12], the Signer computes r, v and u, as shown in eq. 3.11, 3.12 and 3.13:

$$r = e(P_1, P)^k \tag{3.11}$$

  where P is the generator, $P1 \in G$ and $k \in \mathbb{Z}_q^*$

$$v = r \cdot M(H_{\text{DOC}}) \tag{3.12}$$

$$u = SK_{\text{S}} \cdot v + P_1 \cdot k \tag{3.13}$$

- *Step 4:* The Signer forms the complete signature as $Sign = (u||v)$ and encrypts this signature using HTK to produce $ESign = E_{\text{HTK}}(Sign)$. The Signer then sends this encrypted signature to the Signee.

- *Step 5:* Upon receiving, Signee decrypts $ESign$ to retrieve $Sign$ and integrate it with the document, hence completing the handshake. For verification, Signee fetches u and v from $Sign$ and recomputes:

  First, the document hash $H_{\text{DOC}}{}'$ is recomputed using SHA-256, as shown in eq. 3.14:

$$H_{\text{DOC}}{}' = H_{\text{SHA256}}(Doc.) \tag{3.14}$$

  Next, r' is calculated using bilinear pairings, as shown in eq. 3.15:

$$r' = e(u, P) \cdot e(PK_{\text{S}}, P_{\text{pub}})^{-v} \tag{3.15}$$

  Then, the value v' is derived using r' and the document hash, as defined in eq. 3.16:

$$v' = r' \cdot M(H_{\text{DOC}}{}') \tag{3.16}$$

Finally, verification is successful if the computed v' matches the received v, as shown in eq. 3.17:

$$v' == v \tag{3.17}$$

3.5 Security Analysis of the iDSign Framework

The PKG is essential within the iDSign framework and is responsible for generating private keys tailored to the unique identities of participating devices. The PKG is presumed to be trusted, protected, not compromised, and will not begin aggressive assaults. Since PKG's secret master key generates all the private keys, a shady PKG or a malicious individual who obtains the secret master key can potentially execute a successful MiTM attack or create unauthorized private keys to impersonate legitimate users. Similar risks are also present in PKI systems, where compromising a certificate authority (CA) can lead to significant consequences.

1. *Resistance against Man-in-the-Middle-Attack:* The iDSign framework efficiently prevents Man-in-the-Middle (MiTM) attacks due to the powerful mutual authentication provided by iTLS [10]. Consider a scenario in which the attacker receives respective EK_{S} and EK_{D}, attacker can create arbitrary $EK_{\text{S}}^{'}$ and $EK_{\text{D}}^{'}$ to replace the original Ephemeral Keys, and transfer them to the Signee and Signer Devices, respectively. For instance, the attacker can arbitrarily choose x' and y', and substitute $EK_{\text{S}} = x.P$ with $EK_{\text{S}}^{'} = x'.P$ and $EK_{\text{D}} = y.P$ with $EK_{\text{D}}^{'} = y'.P$. Following that, the shared secret the Signer computes is $x.EK_{\text{D}}^{'}||e(x.P_{\text{Pub}} + SK_{\text{S}}, EK_{\text{D}}^{'} + H(ID_{\text{D}}))$. However, though the attacker knows EK_{S} and EK_{D}, the attacker will not be able to compute the shared secret without either of the private keys of both devices.

2. *Perfect Forward Secrecy:* This attribute assures that compromising the over time private keys of either of the communication devices never breaks the integrity of the session key generated during the prior interaction, thus the protection of the sensitive information transmitted previously. The computation of the shared secret key relies not merely on the long-term private key of the involved parties but also on the randomly selected ephemeral secrets by each device. Regardless of whether an intruder discovers the private keys, the intruder also needs to figure out $x.y.P$ from $EK_{\text{D}} = y.P$ and $EK_{\text{S}} = x.P$, which is a Computational Diffie-Hellman (CDH) (refer section 3.3) problem and is independent of long-term private keys. Therefore, an intruder with private keys cannot obtain earlier session keys.

3. *Unique Session Keys:* As the device randomly generates the ephemeral public keys in each connection, two distinct communications generate different and independent session keys. Hence, the intruder cannot get relevant information about additional session keys even if someone stoles the session key.

4. *Resilience to Replay Attack:* The keying information utilized for encrypting the data is established by both devices, hence providing replay protection.

5. *Protected from Impersonation Attacks:* The iDSign framework, due to its usage of iTLS, enables protection against impersonation attacks. Even if an attacker succeeds in compromising a device's long-term private key, the attacker will not

be able to establish a connection with either of the devices. Consider a scenario where an attacker impersonates a Signee and knows the private key of Signer SK_{S}, the ephemeral public key EK_{S}, and the ephemeral secret y' attacker chooses. To compute the shared secret $SS_{\mathrm{D}} = y.EK_{\mathrm{S}}||e(EK_{\mathrm{S}}+H(ID_{\mathrm{S}}), y.P_{\mathrm{Pub}}+SK_{\mathrm{D}})$, attacker must compute $e(EK_{\mathrm{S}}, SK_{\mathrm{D}}) = e(P, PK_{\mathrm{D}})^{x.s}$, However, Signee's private key is not known, thus computing $x.s.P$ from $EK_{\mathrm{S}} = x.P$ and $P_{\mathrm{PUB}} = s.P$ is again a CDH problem.

Chapter 4

Design and Implementation of the Proposed iHDoc Mobile Application

4.1 Introduction

The iHDoc mobile application prototype shows a practical implementation of the iDSign framework, as shown in Figure 4.1, enhanced for secure and lightweight digital document signing in proximity-based mobile environments. A key feature is the utilization of NFC in HCE mode [2], allowing mobile devices to replicate smart cards, hence removing the need for supplementary hardware. NFC's proximity-based communication guarantees a safe, easy, and efficient setup optimal for in-person engagements. NFC enhances security for two-way communication by restricting interactions to close-range exchanges, thereby reducing the risks associated with remote cyberattacks, including eavesdropping and replay attacks. The prototype, constructed on Android, utilizes Bluetooth for large file data transmission and the Java Pairing-Based Cryptography (jPBC) library for strong cryptographic functions, providing a complete, reliable solution [26].

4.2 Related Work

In recent years, mobile digital signing solutions have become increasingly popular, with Adobe Sign [27], Visma Sign [28], and DocuSign [29] emerging as prominent choices. These platforms largely depend on cloud-based architecture and PKI, which, although offering strong security, impose constraints that may impact usability and security, especially in mobile and offline environments. Table 4.1 compares existing digital signature solutions.

Adobe Sign [27] employs PKI for authentication and document signing, which cloud-based certificates or hardware tokens can implement. Nevertheless, PKI systems frequently necessitate complex certificate management and incur considerable processing requirements, making them less suitable for resource-constrained devices. The dependence on a centralized authority for certificate validation makes Adobe Sign prone to network-based attacks and restricts offline capabilities.

Visma Sign [28] depends on strong ID verification methods, such as banking or mobile ID, which require continuous internet connectivity for authentication. The reliance on external identity providers and centralized verification creates network weaknesses, making it inappropriate for environments with restricted connectivity. Although Visma

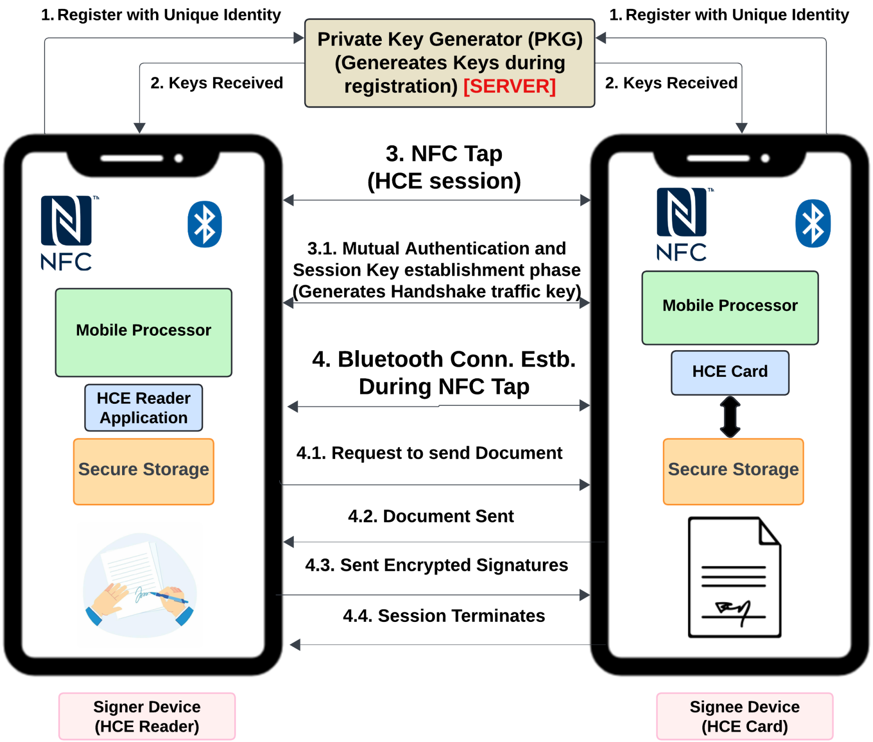

1. Register with Unique Identity
Private Key Generator (PKG) (Genereates Keys during registration) [SERVER]
1. Register with Unique Identity
2. Keys Received
2. Keys Received
3. NFC Tap (HCE session)
NFC
NFC
Mobile Processor
HCE Reader Application
Secure Storage
3.1. Mutual Authentication and Session Key establishment phase (Generates Handshake traffic key)
4. Bluetooth Conn. Estb. During NFC Tap
4.1. Request to send Document
4.2. Document Sent
4.3. Sent Encrypted Signatures
4.4. Session Terminates
Mobile Processor
HCE Card
Secure Storage
Signer Device (HCE Reader)
Signee Device (HCE Card)

Figure 4.1: iHDoc mobile application: Block diagram

Table 4.1: iHDoc mobile application: Comparison of existing digital signature solutions

Existing Solution	**Signature Type**	**Authentication Method**	**Internet Required**	**Encryption Model**	**Limitations**
Adobe Sign [27]	PKI-based digital, Cloud Cert. or tokens	PKI certs, Hardware tokens, Cloud-based tokens	Required	RSA encryption, high computational demand	High processing, Internet dependent
Visma Sign [28]	Strong ID signatures, cloud servers	External ID verification (Banking, Mobile ID)	Mandatory for ID verification	Govt. ID verification	Cloud server dependent, limited offline capability
DocuSign [29]	E-sign, PKI-based digital	SMS, email, third-party integration	Required for auth. and cert. access	RSA encryption, high computational demand	Limited offline access, Cloud dependency

Sign provides secure, regulated authentication, it needs more offline or in-person signing flexibility.

DocuSign [29], a PKI-based service, accommodates several authentication methods like SMS, email, and third-party connections. Nonetheless, its reliance on cloud infrastructure constrains its applicability in offline contexts and presents security vulnerabilities linked to remote authentication.

Although these technologies provide dependable document signing for remote and high-security scenarios, they often rely on constant internet connectivity, making them unsuitable for offline usage. In contrast, the proposed iHDoc mobile application prototype mitigates these limitations by utilizing iDSign framework with low-energy NFC HCE mode [2] for tap-based in-person digital signing. Unlike PKI-based solutions, iHDoc based on iDSign eliminates certificate administration, minimizing computational load and streamlining key management for mobile devices. The NFC HCE mode tap requirement

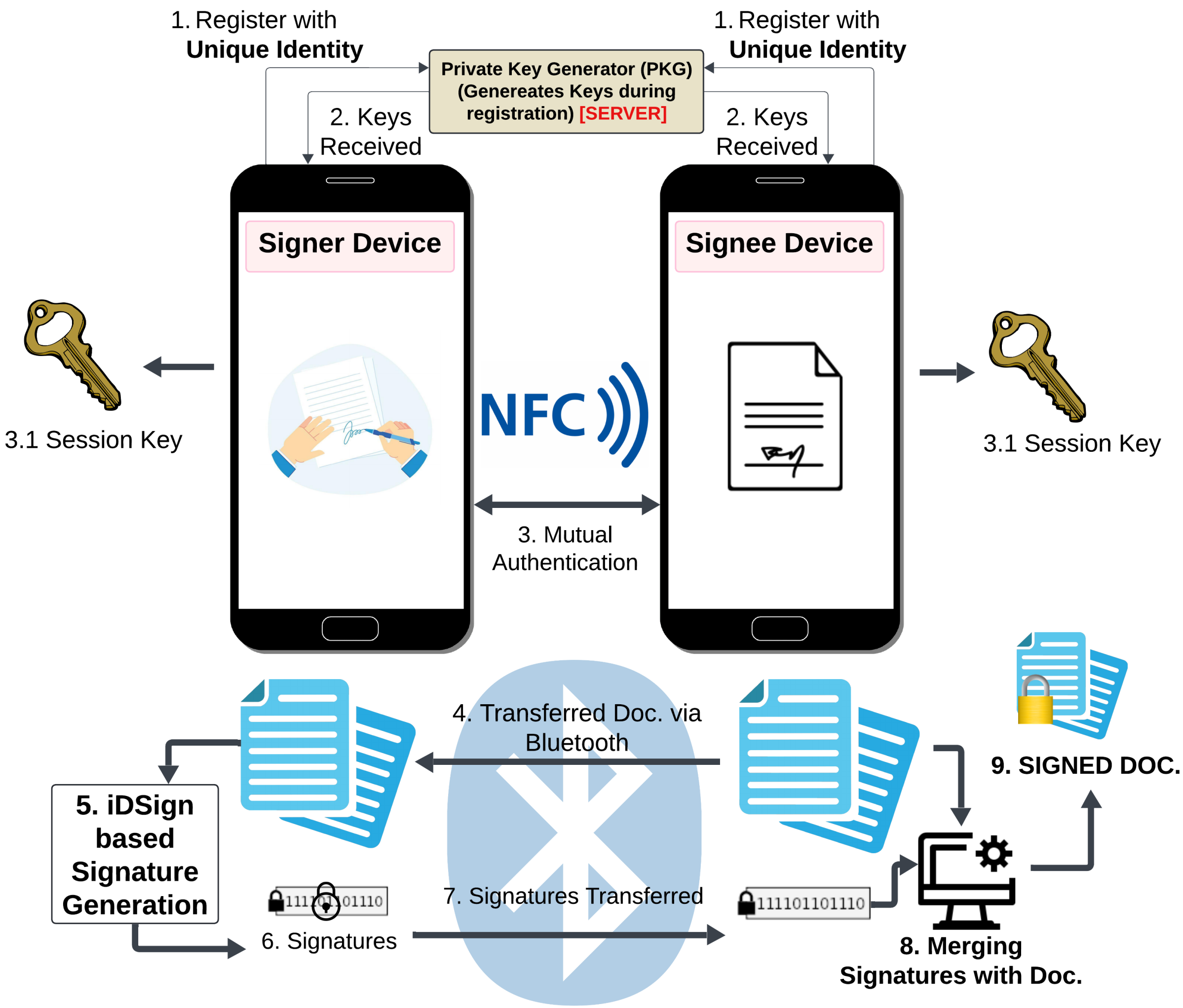


Figure 4.2: iHDoc mobile application: Framework architecture

minimizes proximity attacks such as MiTM attacks. Moreover, iHDoc's offline signing capability makes it well-suited for environments with limited or no connectivity.

4.3 System Architecture and Implementation

The mobile application prototype features an intuitive user interface (see Figure 4.3) designed to streamline the signing process, with distinct Signer and Signee roles in the workflow. This section breaks down the architecture and implementation specifics, demonstrating how each component facilitates secure and efficient in-person digital signing. Figure 4.2 illustrates the process flow for the iHDoc mobile application.

4.3.1 System Components

The iHDoc system consists of the following fundamental components:

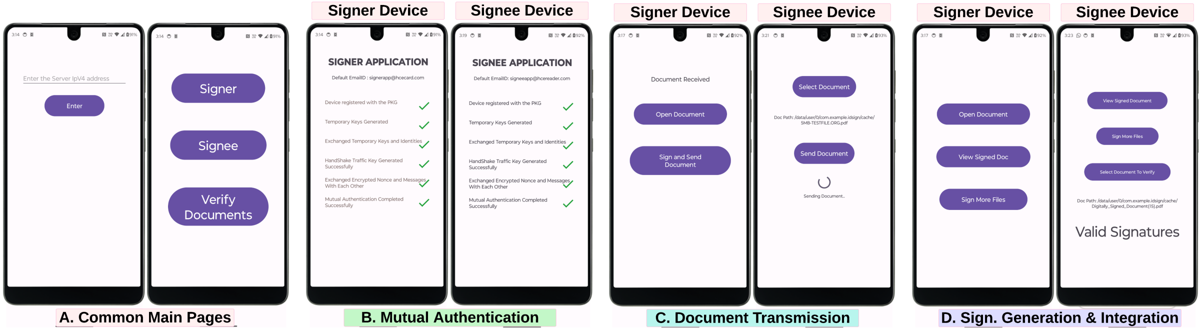
- *Private Key Generator (PKG):* It is a server component that generates and distributes identity-based cryptographic keys.

- *Signer Device:* This device preserves the confidential signing credentials and commences the signing procedure. It functions as the NFC reader in HCE mode [2].
- *Signee Device:* This device requests document signing and receives the signed document. It operates in NFC HCE mode to serve as a virtual card for data transmission.

4.3.2 Workflow Overview

The iHDoc workflow adopts a structured sequence, starting from device registration to completing a digitally signed document. Figure 4.2 shows the details of the iHDoc framework, which utilizes multiple libraries and technologies that work in unison to ensure secure, efficient document signing. The key steps are as follows:

1. *Device Registration with PKG:* The Signer and Signee devices register their unique identities (such as email or phone number) with the PKG. It uses these identities to generate corresponding public and private keys, leveraging IBC.
2. *Keys Reception:* The devices receive their respective keys (private and public) from the PKG.
3. *Mutual Authentication and Session Key Establishment (NFC HCE Session):*
    - Once registered, both devices initiate mutual authentication by tapping the devices, utilizing low-energy NFC HCE mode and iDSign (as shown in Figure 4.3-B).
    - During this tap-based interaction, both devices authenticate each other using iDSign's mutual authentication and exchange ephemeral public keys ($EK_{\mathrm{S}} = x.P$, $EK_{\mathrm{D}} = y.P$), unique identifiers (ID_{S},ID_{D}), nonces (N_{S},N_{D}), and PKG details to establish trust.
    - Both devices independently compute a shared secret SS using bilinear pairing curve operations: $SS_{\mathrm{D}} = y.EK_{\mathrm{S}}||e(EK_{\mathrm{S}} + M(ID_{\mathrm{S}}), y.P_{\mathrm{Pub}} + SK_{\mathrm{D}})$. The shared secret is then processed through an HMAC-based key derivation function (HKDF) to derive the session key $HTK = HKDF(SS, P_{\mathrm{Pub}})$
    - The Signee sends an encrypted message (EFM_{D}) to the Signer, containing a random string (RS), a timestamp, and the incremented nonce (N_{S}+1). The Signer decrypts EFM_{D} using the session key, validates the parameters, and responds with its encrypted message (EFM_{S}) containing similar parameters. Successful validation completes mutual authentication, and the session key secures subsequent communication.
    - In addition to authentication, the Signer's Bluetooth name is shared with the Signee during the NFC tap, facilitating automatic Bluetooth pairing.
4. *Document Transfer via Bluetooth:* The Signee establishes an automated Bluetooth connection and sends the document to the Signer (as shown in Figure 4.3-C).
5. *Digital Signature Generation:* On receiving the document, the Signer uses the Hess IBS [12] scheme to generate the digital signature by utilizing the document's hash, the Signer's private key, and cryptographic parameters managed through the jPBC library [26], which facilitates pairing-based operations for IBC.



Default EmailID : signerapp@hcecard.com

Device registered with the PKG ✓

Temporary Keys Generated ✓

Exchanged Temporary Keys and Identities ✓

HandShake Traffic Key Generated Successfully ✓

Exchanged Encrypted Nonce and Messages With Each Other ✓

Mutual Authentication Completed Successfully ✓

Default EmailID: signeeapp@hcereader.com

Device registered with the PKG ✓

Temporary Keys Generated ✓

Exchanged Temporary Keys and Identities ✓

HandShake Traffic Key Generated Successfully ✓

Exchanged Encrypted Nonce and Messages With Each Other ✓

Mutual Authentication Completed Successfully ✓

Document Received

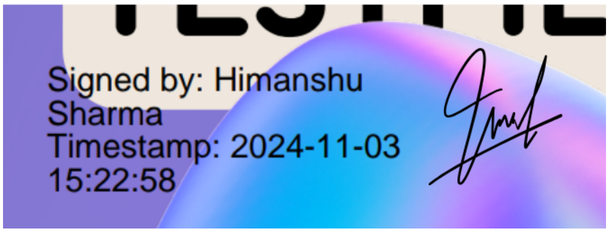
Doc Path: /data/user/0/com.example.idsign/cache/5MB-TESTFILE.ORG.pdf

Sending Document..

Doc Path: /data/user/0/com.example.idsign/cache/Digitally_Signed_Document(15).pdf

Valid Signatures

Figure 4.3: iHDoc mobile application: Screenshots of the application user interface



Signed by: Himanshu Sharma
Timestamp: 2024-11-03 15:22:58

Figure 4.4: iHDoc mobile application: Sample appearance of digital signatures in doc.

6. Signer then encrypts the signatures with the previously generated session key to guarantee secure transmission to the Signee device.

7. *Signature Transmission:* The Signer transmits the encrypted signature to the Signee device over the secure Bluetooth channel.

8. *Signature Integration:* The Signee decrypts signatures using the session key, incorporates it into the original document, and completes the digital signing process. As shown in Figure 4.4, the digital signature includes identifying information and a timestamp for authenticity within the document. The user can continue signing more documents or end the session (as shown in Figure 4.3-D).

9. *Signed Document Storage and Verification:* The final signed document is stored locally and can be verified by any device using the Signer's public key.

4.3.3 Technologies and Libraries Used:

This section breaks down the fundamental technologies and libraries incorporated into the iHDoc prototype, clarifying their functions in secure digital document signing on Android devices.

1. *Android NFC with HCE:* Low-energy NFC technology in HCE mode facilitates proximity, tap-based interactions between Android devices, emulating a physical smart card. This configuration ensures secure session initiation by minimizing vulnerability to man-in-the-middle attacks.

2. *Bluetooth for Data Transfer:* Bluetooth is used for efficient data transmission following iDSign based authentication. This method utilizes Bluetooth's stability and bandwidth for transferring larger files, such as PDF documents, post-authentication.

3. *jPBC Library [26]:* The Java Pairing-Based Cryptography (jPBC) library is an essential element of the iHDoc system, facilitating all cryptographic functions based on IBC. The jPBC library enables bilinear pairing operations crucial for IBC, facilitating secure connections and digital signatures based on user identities instead of conventional public-key certificates. This pairing-based methodology, crucial to iHDoc, facilitates the protocol's lightweight yet safe cryptographic requirements, from mutual authentication to document signing. The jPBC library minimizes the computational and storage requirements commonly linked to certificate-based systems, enabling iHDoc to provide both security and efficiency, making it a perfect option for mobile applications.

4. *Bouncy Castle Library [30]:* Bouncy Castle provides essential cryptographic operations, including the HKDF (HMAC-based Key Derivation Function), which generates the symmetric session key (HTK) during the mutual authentication phase.

5. *iText Library [31]:* iText facilitates fast and seamless PDF file manipulation within the iHDoc system, offering tools for embedding and validating digital signatures.

6. *Spring Framework for Local Server Setup [32]:* A local server built with the Spring framework operates as the PKG, making and distributing keys based on identity. When devices send identity information (e.g., email or phone number) to the server, it provides the associated identity-based cryptographic key pairs, facilitating iHDoc based on the iDSign framework.

Chapter 5

Results

5.1 Performance Analysis of the iDSign Framework

The performance analysis of the iDSign framework and its prototype implementation, iHDoc, is essential to demonstrate their efficiency, security, and practicality. The evaluation includes qualitative and quantitative assessments, measuring computational overhead, memory usage, and cryptographic strength while comparing them with existing solutions. This section highlights the proposed framework's lightweight nature and the prototype's secure, efficient operations under real-world conditions.

5.1.1 Qualitative Analysis

The design of iDSign addresses several essential areas to boost overall performance and security:

- *Lightweight Authentication:* iDSign's use of IBC removes the need for heavy certificate exchange, reducing communication and computational costs compared to traditional PKI methods. This efficiency is crucial for resource-limited devices.

- *SE Integration:* iDSign framework leverages the Secure Element's hardware acceleration and enclosed environment to securely store cryptographic credentials, accelerating the speed of signing operations while boosting security by rendering cryptographic keys tamper-resistant.

- *Adaptability to Multiple Scenarios:* iDSign's versatile design enables for deployment across many communication interfaces, such as low-energy NFC, Bluetooth, and TCP/IP Protocols, providing a seamless and intuitive user experience while ensuring compatibility with existing infrastructure and supporting both remote and in-person signing use cases.

The added features make iDSign especially appropriate for situations demanding rapid, efficient, and reliable digital signatures.

Table 5.1 compares protection against possible attacks between the proposed framework and other existing schemes. iDSign framework provides a novel combination of mutual authentication, MiTM attack protection, data privacy through robust authentication and integration of SE, key compromise protection with ephemeral keys, and the capability for Perfect Forward Secrecy. This comprehensive approach addresses a wider

Table 5.1: iDSign performance analysis: Qualitative analysis of proposed framework

Scheme	MA	MiTM	DP	SKS	KC	RA	PFS	IA
AuthPaper [5]	✓	✓	✓	*	✓	✓	*	✓
DSign [4]	×	×	×	*	×	*	*	×
BioSign [22]	✓	✓	*	✓	✓	✓	*	✓
PDFGuard [6]	×	×	✓	*	✓	*	*	✓
ECDoc [7]	×	×	✓	*	×	×	*	×
Proposed iDSign	✓	✓	✓	✓	✓	✓	✓	✓

MA: Mutual Auth., MiTM: Man-in-the-Middle Attack, DP: Data Privacy, SKS: Session Key Security, KC: Key Compromise, RA: Replay Attack, PFS: Perfect Forward Secrecy, IA: Impersonation Attack, ✓: Protected, ×: Vulnerable, *: Not Mentioned in the scheme

range of security vulnerabilities than many compared approaches, making iDSign particularly suitable for circumstances where robust authentication and secure communication are vital.

5.1.2 Quantitative Analysis

The quantitative analysis emphasizes two critical elements: communication and computation costs associated with iDSign and other digital signature schemes.

Communication Cost:

This analysis assumes that a 50KB document is submitted to either a central server or portal or directly to the Signer's device based on the type of solution used for generating the digital signature.

Table 5.2 compares the approximate communication cost for data communicated for a document with certain assumptions. It presents the time for the following:

- *MetaData (MD):* This column includes headers, IDs, and other control information for each communication step. The values above are rough approximations.
- *Mutual Authentication (MA):* This column shows the approximate Communication overhead necessary to verify both devices' identities.
- *Document (Optional) + Sign Received:* Some approaches re-transmit the document integrated with a digital signature. iDSign only sends signature records, minimizing overhead.

Table 5.2 displays anticipated data sizes for each communication stage, using typical values for cryptographic primitives and message overhead. It is vital to remember that the transmission cost can vary based on the chosen cryptographic techniques and the size of the signed documents. The iDSign framework leverages lightweight mutual authentication utilizing IBC, delivering substantial reductions in communication overhead compared to the standard certificate-based techniques. Certificate sizes range from hundreds of bytes to several kilobytes [10], generating severe delays during transmission

Table 5.2: iDSign performance analysis: Approximate communication cost comparison for document of size 50KB

Scheme	**Type of Service**	**MD (bytes)**	**MA (bytes)**	**Doc. (Opt) + Sign (bytes)**	**TCC (bytes)**
DSign [4]	Web-Based	200	*	51024	51224
BioSign [22]	Software	1072	200	51300	52572
PDFGuard [6]	Web-Based	100	*	50320	50420
ECDoc [7]	Web-based	100	*	50600	50700
iDSign	Flexible	20	950	300	1270

MD: MetaData, MA: Mutual Auth., Doc. (Opt) + Sign: Document (Optional) + Signature received, TCC: Total communication Cost, *: Not Mentioned in the Scheme

and authentication. In Table 5.2, the analysis indicates that iDSign incurs the lowest total communication cost, amounting to merely 1270 bytes, attributable to its lightweight mutual authentication approach and optimized signature transmission. This reduction achieves a 97% decrease in overhead when compared to DSign and a 75% decrease relative to PDFGuard, demonstrating its effectiveness in environments with constrained bandwidth. iDSign enhances efficiency in low-power environments by transmitting just signature records rather than complete documents, which reduces data transmission without compromising security.

Computation Cost:

Multiprecision Integer and Rational Arithmetic Library (MIRACL) [33] is an open-source library specifically created to simplify the process of testing cryptographic protocols. It provides a robust platform for performing complex arithmetic operations on large integers and rational numbers, essential in various cryptographic applications, such as public key cryptography. This work uses the methodology outlined by Yu et al. [34] based on MIRACL to derive the computation costs. Table 5.3 assumes the values of the following operations: C_{BP}: Computation of Bilinear Pairing ≈ 3.002 ms [34], C_{KH}: Computation of obtaining session key from Diffie-Hellman Algorithm ≈ 2 ms, C_{SED}: Computation of Symmetric Encryption/Decryption ≈ 0.012 ms (for example, Advanced Encryption Standard (AES) [35]), C_{H}: Computation of Hash Function ≈ 0.309 ms (for example, Secure Hash Algorithm (SHA-256) [36]), C_{QR}: Computation of QR generation ≈ 30 ms [37], C_{ET}: Computation of Euler's Totient Function ≈ 2 ms [6], C_{KE}: Computation of ElGamal Encryption ≈ 0.522 ms (It is an asymmetric encryption algorithm with similar computation cost), C_{AED}: Computation of Asymmetric Encryption/Decryption ≈ 0.522 ms (for example, RSA [38]).

Table 5.3 illustrates the computational costs associated with various schemes. Although iDSign has a slightly higher computational time of 12.67 ms due to bilinear pairing and SE operations, it surpasses other schemes in terms of security by integrating mutual authentication and forward secrecy. While ECDoc achieves the lowest computation cost, it lacks robust mutual authentication, making it less secure. The integration of SE in iDSign offers various benefits, such as hardware acceleration and enhanced security through

Table 5.3: iDSign performance analysis: Approximate computation cost comparison

Scheme	Computation Cost	Estimated Time(ms)
DSign [4]	$1C_{\mathrm{H}} + 1C_{\mathrm{QR}}$	30.30
BioSign [22]	$1C_{\mathrm{KH}} + 2C_{\mathrm{KE}} + 2C_{\mathrm{SED}} + 3C_{\mathrm{H}}$	3.99
PDFGuard [6]	$2C_{\mathrm{AED}} + 1C_{\mathrm{ET}} + 2C_{\mathrm{H}}$	3.66
ECDoc [7]	$2C_{\mathrm{AED}} + 2C_{\mathrm{H}}$	1.66
iDSign	$4C_{\mathrm{BP}} + 2C_{\mathrm{H}} + 4C_{\mathrm{SED}}$	12.67

C_{BP}: Computation of Bilinear Pairing, C_{KH}: Computation of obtaining session key from Diffie-Hellman Algo., C_{KE}: Computation of Elgamal Encryption, C_{SED}: Computation of Symmetric Encryption/Decryption, C_{H}: Computation of Hash Function, C_{QR}: Computation of QR generation, C_{ET}: Computation of Euler's Totient Function, C_{AED}: Computation of Asymmetric Encryption/Decryption

tamper-resistant storage, which optimize cryptographic operations and enhance overall performance. While iDSign demands the most computational power, it balances computational efficiency and improved security, justifying the additional resources required to ensure the integrity and trustworthiness of digital signatures.

5.2 Performance Analysis of the iHDoc mobile application prototype

This section evaluates the performance of the iHDoc prototype, designed by integrating the iDSign framework with low-energy NFC HCE technology for proximity-based digital signing of documents. To assess the efficiency, iHDoc's mutual authentication based on the iDSign framework is compared with RSA-based mutual authentication, ensuring a balanced comparison. Key metrics include timing and storage requirements, emphasizing the lightweight nature of iDSign framework for mobile use.

5.2.1 Timing Comparison of Core Components

Table 5.4 compares the approximate time taken for different components of iHDoc based on iDSign and RSA [39] when processing a document of 1MB size. The components analyzed include Mutual Authentication, Bluetooth File Transfer, Signature Generation, and Signature Integration.

- *Mutual Authentication:* iHDoc with iDSign achieves a faster mutual authentication time (0.479 sec) than RSA-based authentication (0.702 sec) due to the absence of certificate verification in iDSign, thus reducing computational overhead.

- *Bluetooth File Transfer:* The time for Bluetooth file transfer remains similar in both configurations, as Bluetooth communication is independent of the cryptographic method.

Table 5.4: iHDoc performance analysis: Approximate timing comparison of diff. components for document of size 1MB

Scheme	**Mutual Auth. (sec)**	**Bluetooth File Transfer (sec)**	**Signature Generation (sec)**	**Signature Integration (sec)**	**Total (sec)**
iHDoc based on iDSign	0.479	11.170	0.207	0.421	**12.277**
RSA [39]	0.778	11.19	0.232	0.428	**12.628**

Table 5.5: iHDoc performance analysis: Approximate credentials storage requirements

Scheme	**Public Key Size (bytes)**	**Private Key Size (bytes)**	**Certificate Size (bytes)**	**Symmetric Session Key Size (bytes)**	**Ppub (bytes)**	**P (bytes)**	**Total (bytes)**
iHDoc based on iDSign	128	20	-	128	128	128	**532**
RSA [39]	256	256	1024	128	-	-	**1664**

Ppub: Master Public Key, P: Generator in iDSign

- *Signature Generation:* iHDoc with iDSign also performs faster signature generation (0.207 sec) compared to RSA-based approach (0.232 sec), reflecting the efficiency of the Hess IBS scheme used in iDSign framework.

- *Signature Integration:* The time required for signature integration is slightly lower in iHDoc with iDSign (0.421 sec) compared to RSA (0.428 sec), benefiting from the streamlined IBC approach used in iDSign framework.

The results in Table 5.4 demonstrate that iHDoc based on iDSign offers reduced processing times in the mutual authentication and signature generation phases, emphasizing the advantages of lightweight cryptography for digitally signing documents on mobile devices.

5.2.2 Storage Requirements

Table 5.5 compares storage requirements for credentials and cryptographic keys in the iHDoc prototype based on the iDSign framework versus RSA [39] certificate-based keys. The RSA keys requires more storage due to the inclusion of public/private key pairs and certificates, whereas iHDoc based on the iDSign framework utilizes IBC which significantly reduces storage requirements by eliminating certificates.

- *RSA Key and Certificate Storage:* In RSA-based approach, each device requires storage for RSA public/private keys and certificates and requires approximately 1664 bytes for storage.

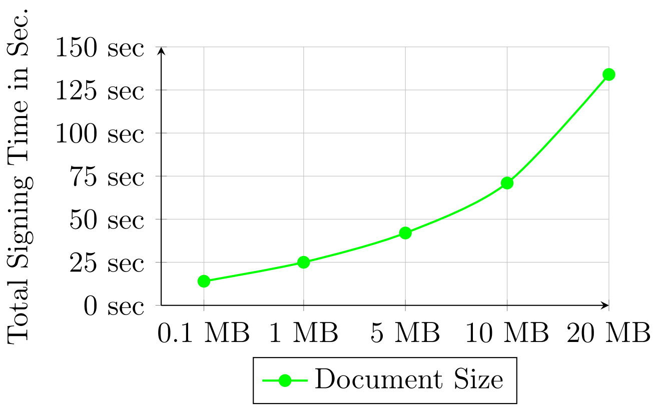


Figure 5.1: iHDoc performance analysis: Relationship between total signing time vs doc. size

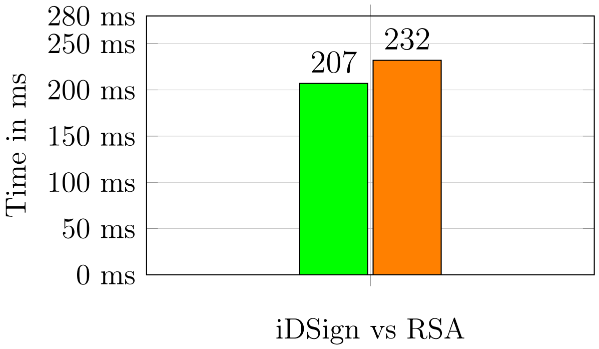


Figure 5.2: iHDoc performance analysis: Comparison of signature generation time with RSA

- *iHDoc Key Storage:* iHDoc due to iDSign integration eliminates certificates, reducing storage needs to only 532 bytes for storing public and private keys, the master public key (Ppub), and the generator (P). Hence, iDSign framework is more suitable for mobile devices with limited storage capacity.

As shown in Table 5.5, the total storage requirement for iHDoc based on iDSign is 532, significantly lower than the 1664 bytes required for the RSA-based approach. This reduction in storage requirements is critical for mobile devices, where storage space is often limited.

5.2.3 Document Size vs. Signing Time

Figure 5.1 illustrates the relationship between document size and total signing time in iHDoc based on iDSign. As document size increases, the time taken for signing also increases, largely due to Bluetooth transfer time. For smaller documents (e.g., 0.1 MB), the signing time is relatively low (around 14 seconds), but for larger documents (e.g., 20 MB), the signing time increases substantially (up to 134 seconds). This graph highlights iHDoc's scalability and the impact of document size on overall performance.

5.2.4 Signature Generation Time Comparison

Figure 5.2 compares signature generation time between iHDoc based on iDSign and RSA-based approach. The signature generation time in iDSign is approximately 207 ms, while RSA requires 232 ms. This performance difference highlights the efficiency of the Hess IBS scheme used in iDSign, making it well-suited for mobile environments with limited computational resources.

Chapter 6

Conclusion and Future Work

This thesis introduces the novel iDSign framework as a secure, lightweight, and flexible solution for the digital signature of documents, compatible with resource-constrained devices. It supports multiple communication interfaces such as NFC, Bluetooth, and TCP/IP. The framework addresses the significant shortcomings of current PKI-based systems, such as complex certificate management, which are prone to several attacks like MiTM and rely on continuous network connectivity. iDSign utilizes IBC and a modified lightweight iTLS protocol to enable certificate-free mutual authentication and efficient cryptographic operations. To validate the iDSign framework in a practical context, the iHDoc mobile application based on iDSign is designed and implemented using NFC HCE technology to enable secure proximity-based communication and mitigate vulnerabilities like MiTM attacks. The application enables tap-to-sign architecture and operates in offline contexts. Performance analysis compares the iHDoc based on iDSign with RSA-based mutual authentication. Results indicate that the iDSign framework significantly reduces mutual authentication and digital signing time compared to the RSA-based approach, thus making it suitable for resource-limited and offline environments.

Future work focuses on exploring the integration of the iDSign framework with smart cards and remote devices. Smart cards offer a secure, portable medium for storing cryptographic keys, enabling digital signing by tapping the card on an NFC-enabled device. Additionally, expanding iDSign to support secure document signing on remote devices will enhance its versatility and enable deployment in enterprise, academic, and governmental workflows, where remote interactions require scalable and robust cryptographic performance.

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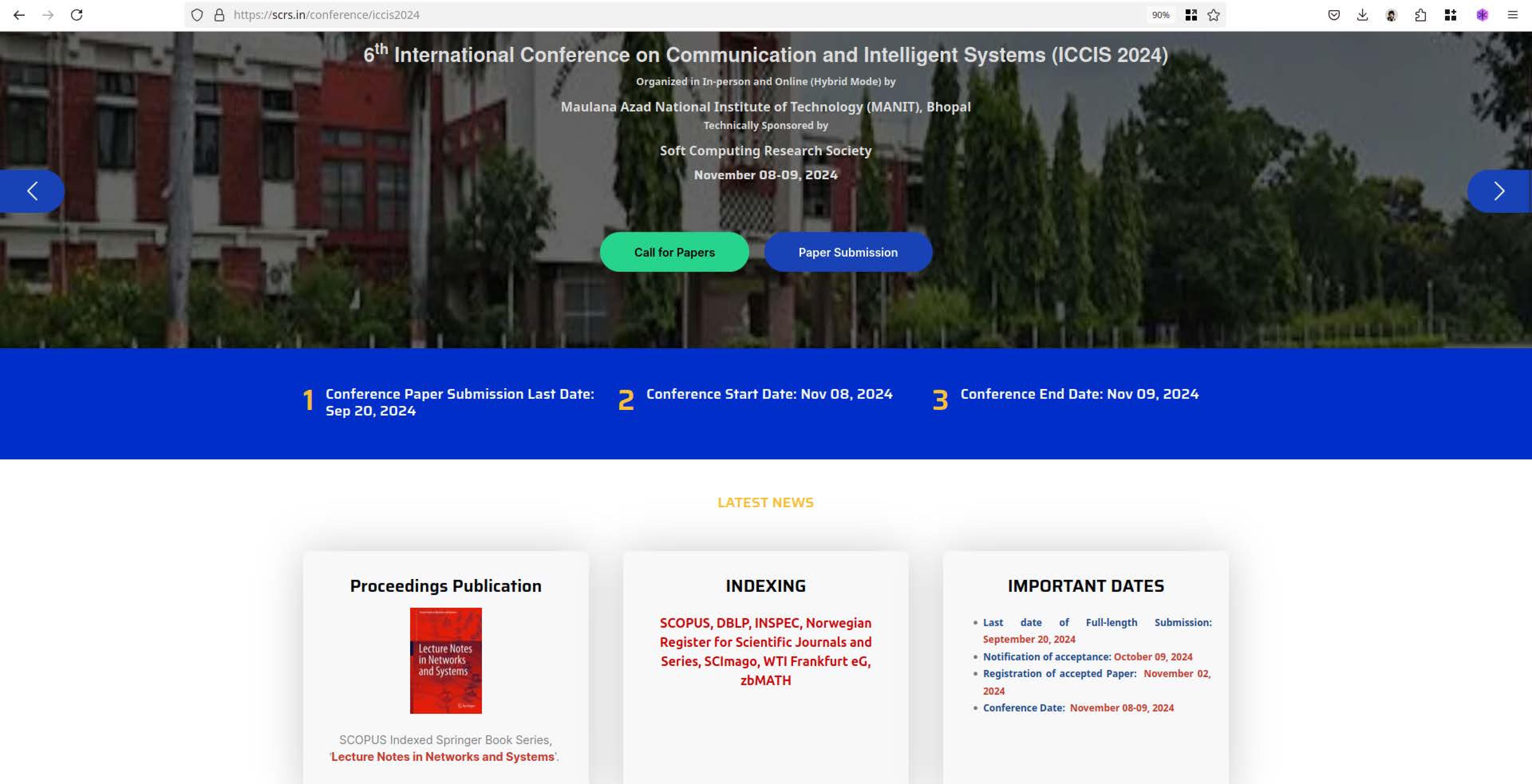

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Microsoft CMT <email@msr-cmt.org> Thu, Oct 10, 2024 at 10:58 PM
Reply-To: ICCIS SCRS <scrs.iccis@gmail.com>
To: Himanshu Sharma <himanshusharma_23swe18@dtu.ac.in>

Dear Himanshu Sharma,

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We are pleased to inform you that based on reviewers’ comments, your paper titled "iDSign: Secure Lightweight Digital Document Signatures Framework with Mutual Authentication and Identity-Based Cryptography" has been accepted for presentation during ICCIS 2024, and publication in the proceedings to be published in Scopus-indexed Springer Book Series "Lecture Notes in Networks and Systems" subject to the condition that you submit a revised version as per the comments, available at Authors CMT account. It is also required that you prepare a response to each comment from the reviewer and upload it as a separate file along with the revised paper.

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This is to certify that **Himanshu Sharma** has presented the paper titled **IDsign: Secure Lightweight Digital Document Signatures Framework with Mutual Authentication and Identity-Based Cryptography** authored by **Himanshu Sharma, Divyashikha Sethia** in the 6th International Conference on Communication and Intelligent Systems (ICCIS 2024) held during November 08-09, 2024.

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DECLARATION

I hereby certify that the work which is presented in the Major Project-II entitled **iDSign: A Secure Lightweight NFC-Based Framework to Tap and Digitally Sign Documents** in fulfillment of the requirement for the award of the Degree of Master of Technology in Software Engineering and submitted to the Department of Software Engineering, Delhi Technological University, Delhi is an authentic record of my own, carried out during a period from January to May 2025 under the supervision of **Dr. Divyashikha Sethia**.

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Title of the Paper: **iHDoc: Secure NFC Mobile-based Digital Document Signatures Prototype**
Author names (in sequence): Himanshu Sharma, Dr. Divyashikha Sethia
Name of Conference/Journal: 2025 INTERNATIONAL CONFERENCE ON INTELLIGENT CONTROL, COMPUTING AND COMMUNICATIONS (IC3 2025)
Conference dates with venue: 13-14th February 2025, Mathura, Uttar Pradesh, India
Status of paper (Communicated/Accepted/Published): Published
Date of paper communication: November 20, 2024
Date of paper acceptance: January 14, 2025
Date of paper publication: April 16, 2025

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To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I further certify that the publication and indexing information given by the students is correct.

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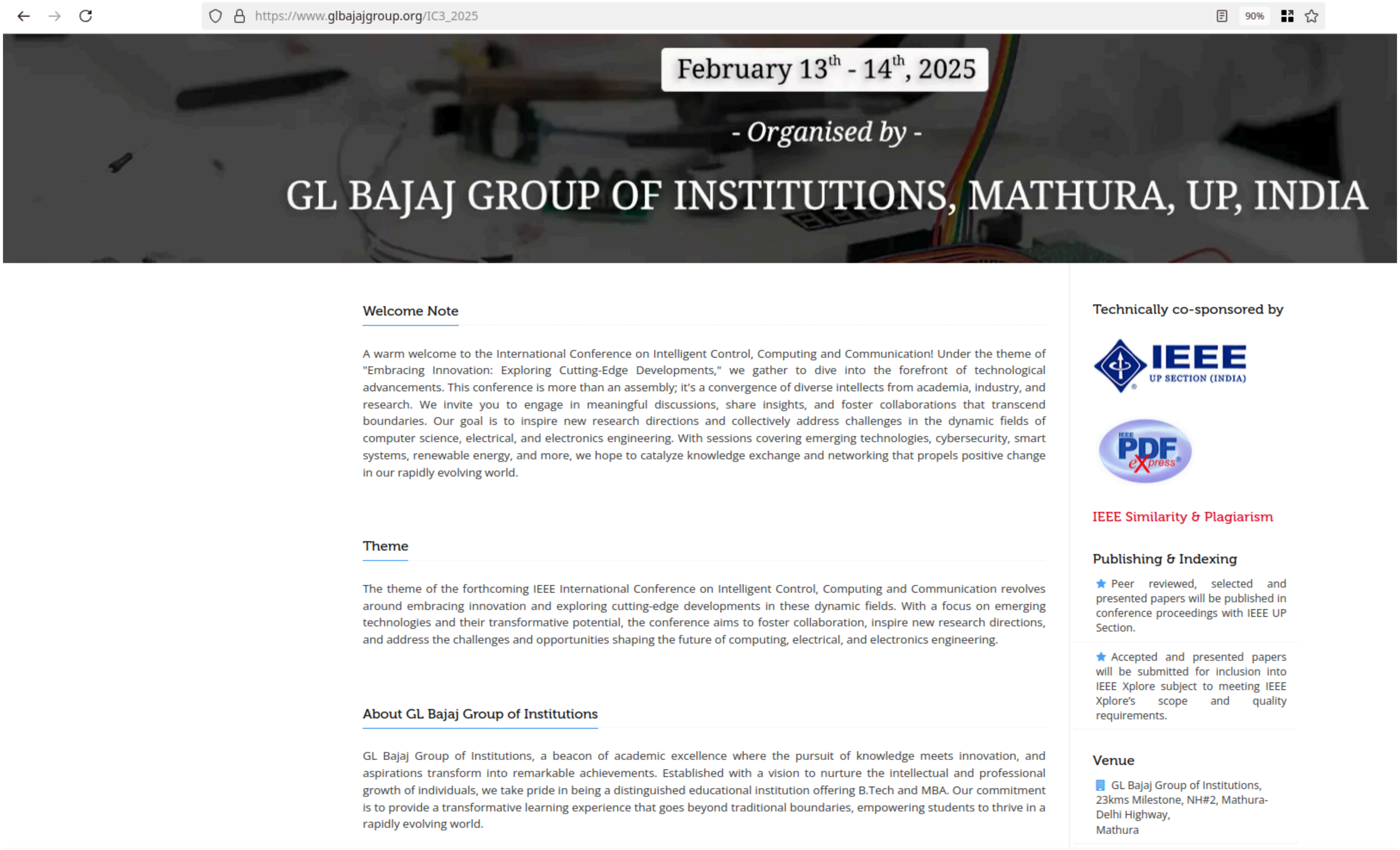

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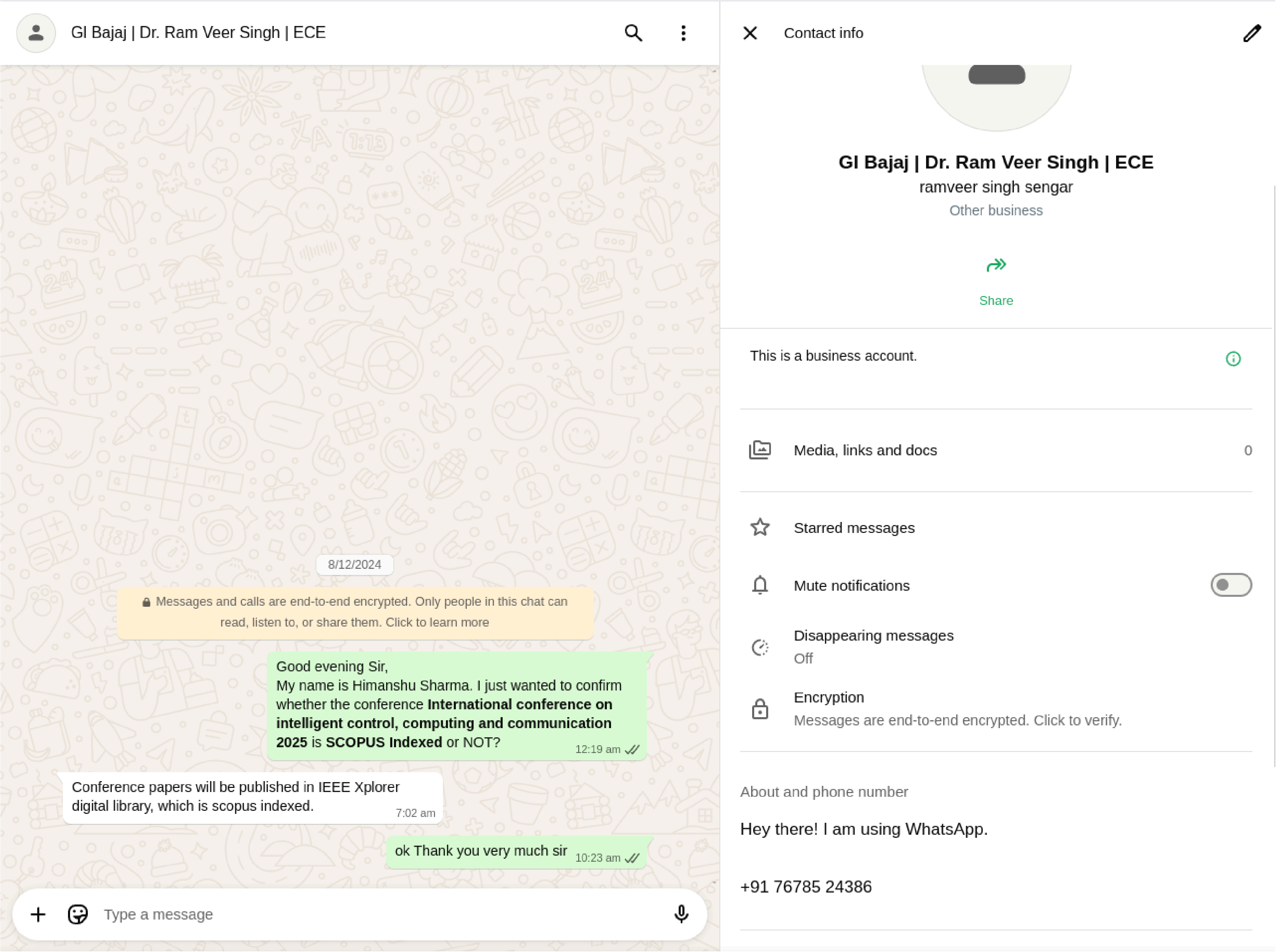

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The following submission has been created.

Track Name: Communications and Networking

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Paper Title: iHDoc: Secure Mobile-based Digital Document Signatures Framework using Host Card Emulation Tap and Lightweight Mutual Authentication

Abstract:

This paper introduces the prototype implementation and assessment of iHDoc, a lightweight framework for secure digital document signing on mobile devices, which is based on the previously proposed iDSign framework (accepted, to be published). The original study laid the theoretical foundation for a versatile framework for safe digital document signing utilizing identity-based cryptography and lightweight mutual authentication through a modified lightweight identity-based Transport Layer Security (iTLS) protocol. This paper builds upon the prior research by employing the framework on mobile devices through native Android development and utilizing NFC-based host card emulation (HCE) for secure session initiation via NFC tap and Bluetooth for effective data transfer. The prototype utilizes the Hess Identity-Based Signature (IBS) technique for speedy and efficient signing, making it suitable for resource-constrained devices. The comparative performance assessment with the RSA-based counterpart, iHDoc_RSA, demonstrates that the iHDoc framework attains faster execution times and decreased storage requirements. The iText library facilitates PDF manipulation and enables the smooth integration of digital signatures. The findings indicate that iHDoc provides both security and performance benefits, making it an effective solution for mobile document signing. Future endeavours will focus on real-world deployment and improved compatibility among platforms.

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Reply-To: "Prof. Neeta Awasthy" <mandhir.verma@glbitm.ac.in>
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Dear Himanshu Sharma,

Congratulations! On behalf of the "2025 International Conference on Intelligent Control, Computing and Communications (IC3)" Technical Program Committee (TPC), we are pleased to inform you that your paper entitled (Paper Id- 60)"iHDoc: Secure NFC Mobile-based Digital Document Signatures Prototype" has been accepted as a REGULAR paper for presentation at the IC3-2025 dated 13-14 February, 2025. All accepted and presented papers will be submitted to IEEE for possible inclusion on IEEE Xplore.

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iHDoc: Secure NFC Mobile-based Digital Document Signatures Prototype

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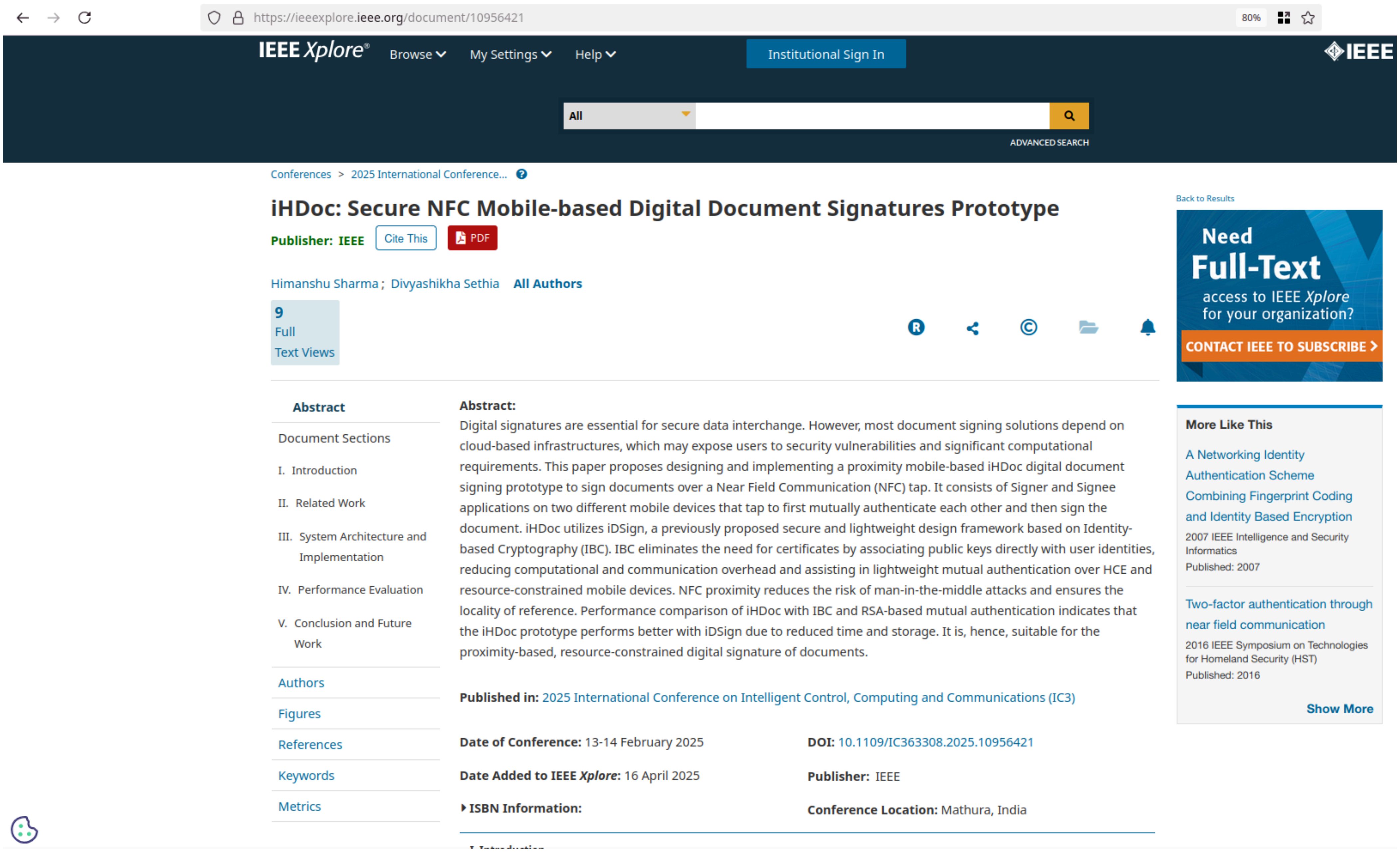

iHDoc: Secure NFC Mobile-based Digital Document Signatures Prototype

Publisher: IEEE

Himanshu Sharma ; Divyashikha Sethia **All Authors**

9 Full Text Views

Abstract
Document Sections
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Abstract:
Digital signatures are essential for secure data interchange. However, most document signing solutions depend on cloud-based infrastructures, which may expose users to security vulnerabilities and significant computational requirements. This paper proposes designing and implementing a proximity mobile-based iHDoc digital document signing prototype to sign documents over a Near Field Communication (NFC) tap. It consists of Signer and Signee applications on two different mobile devices that tap to first mutually authenticate each other and then sign the document. iHDoc utilizes iDSign, a previously proposed secure and lightweight design framework based on Identity-based Cryptography (IBC). IBC eliminates the need for certificates by associating public keys directly with user identities, reducing computational and communication overhead and assisting in lightweight mutual authentication over HCE and resource-constrained mobile devices. NFC proximity reduces the risk of man-in-the-middle attacks and ensures the locality of reference. Performance comparison of iHDoc with IBC and RSA-based mutual authentication indicates that the iHDoc prototype performs better with iDSign due to reduced time and storage. It is, hence, suitable for the proximity-based, resource-constrained digital signature of documents.

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