

A Survey on Decentralized Identifiers and Verifiable Credentials

Carlo Mazzocca , Abbas Acar , Selcuk Uluagac , Rebecca Montanari , Paolo Bellavista , Mauro Conti 

Abstract—Digital identity has always been one of the keystones for implementing secure and trustworthy communications among parties. The ever-evolving digital landscape has undergone numerous technological transformations that have profoundly reshaped digital identity management, leading to a major shift from centralized to decentralized identity models. The latest stage of this evolution is represented by the emerging paradigm of Self-Sovereign Identity (SSI), which gives identity owners full control over their data. SSI leverages Decentralized Identifiers (DIDs) and Verifiable Credentials (VCs), which have been recently standardized by the World Wide Web Consortium (W3C). These technologies have the potential to build more secure and decentralized digital identity systems, significantly strengthening communication security in scenarios involving many distributed participants. It is worth noting that use of DIDs and VCs is not limited to individuals but extends to a wide range of entities including cloud, edge, and Internet of Things (IoT) resources. However, due to their novelty, existing literature lacks a comprehensive survey on DIDs and VCs beyond the scope of SSI. This paper fills this gap by providing a comprehensive overview of DIDs and VCs from multiple perspectives. It identifies key security threats and mitigation strategies, analyzes available implementations to guide practitioners in making informed decisions, and reviews the adoption of these technologies across various application domains. Moreover, it also examines related regulations, projects, and consortiums emerging worldwide. Finally, it discusses the primary challenges hindering their real-world adoption and outlines future research directions.

Index Terms—Decentralized Identifiers (DIDs), Verifiable Credentials (VCs), Self-Sovereign Identity (SSI), Digital Identity, Decentralized Identity.

I. INTRODUCTION

The recent proliferation of digital services accessible through a network connection has led to an unprecedented increase in the number of digital identities [1]. As a result, the vast majority of the world's population owns at least one digital identity, which serves as the key to unlocking a multitude of online capabilities and services. However, the concept of digital identity extends far beyond the identification of human beings [2]. With the widespread adoption of the

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Internet of Things (IoT) and the power of the 5th generation (5G) networks, coupled with the upcoming advent of the 6th generation (6G) networks, there has been a remarkable increase in the number of connected devices [3]. These devices require unique digital identities to enable their participation in the digital ecosystem, such as establishing secure communications.

Digital identification has always been a primary concern, as evidenced by the numerous solutions that have emerged over the years. Indeed, the way an entity proves ownership of a digital identity can be affected by a wide range of vulnerabilities [4]. Centralized identity providers represent a major weakness of traditional identification methods. Information stored in centralized data repositories can potentially lead to serious data breaches, resulting in significant loss of personal data and damage to stakeholders' reputations [5], [6]. In addition, centralized identity management systems rely on specific identity service nodes, making them susceptible to the single point of failure problem [7].

The advent of federated identity systems has addressed some of these weaknesses along with scalability needs [8]. The principal advantage of this identity model lies in empowering users to seamlessly access multiple services using the same identity. This identification paradigm relies on mutual trust among various parties, wherein verification is distributed across all identification systems or entities that mutually accept the standards employed by each system. In a typical federated scenario, users authenticate themselves against a singular authority, referred to as the identity provider, allowing them to access all other applications on its behalf. Despite representing an advance, federated identity still raises significant concerns regarding user privacy. Specifically, this model hinges on a certain level of trust in identity providers, and individuals retain limited control over their data.

Therefore, the increasing use of online services, the growing decentralization, as well as the rising awareness of the drawbacks of traditional methods are paving the way to more secure and privacy-preserving methods. In this direction, supported by the current laws and regulations such as the European General Data Protection Regulation (GDPR) [9], the concept of *Self-Sovereign Identity* (SSI) [10] is gaining significant interest from both the academic and industrial worlds.

SSI is based on the idea that an individual should have full control over their information without being forced to outsource data to any centralized authority or third party. With an SSI, users can directly store their identity data and determine how much of them they wish to share. In this way, they can decide with whom they share their data. A funda-

TABLE I
SUMMARY OF SURVEYS IN THE FIELD.

Year	Ref.	Summary of the Work
2021	Cucko et al. [13]	A systematic mapping study on SSI. The study outlines that DIDs and VCs are discussed in most papers addressing SSI. The paper mainly provides insights into trends and demographics of SSI works.
2021	Soltani et al. [14]	A survey on the SSI ecosystem. The work mainly reviews literature related to SSI. It reports a few available implementations and briefly discusses related regulations in Europe and the United States.
2022	Bai et al. [15]	A concise survey on the use of blockchain in SSI. The concept of DIDs and VCs is only presented as the foundational technologies of SSI, without delving into an examination of relevant research papers.
2022	Schardong et al. [16]	A systematic review and mapping of theoretical and practical advances in SSI. The paper comprehensively discusses how DIDs and VCs can be employed in SSI systems, and also considers a few other application domains.
2023	Ernstberger et al. [17]	A systematization of knowledge on data sovereignty, with a focus on decentralized identity, decentralized access control, and policy-compliant decentralized computation. The paper also outlines key security and privacy properties, along with open challenges in the field.
2024	Krul et al. [18]	A systematization of knowledge based on trust requirements and assumptions of SSI elements. The work identifies threats in SSI, potential mitigation, available implementations, and some challenges.
2024	Tan et al. [19]	A systematic review and analysis of SSI solutions based on a set of research questions. The paper reports the main regulations and policies across Europe and the U.S., as well as a few open challenges.
2024	Satybaldy et al. [20]	A systematic literature review on SSI systems with particular emphasis on the main open challenges. It also reports a few available implementations.
Now	Our Survey	A comprehensive survey on DIDs and VCs, covering all key aspects, including threats and mitigations, primary implementations, applications across diverse domains, and emerging regulations/initiatives proposed by governments and organizations.

TABLE II
COMPARISON OF SURVEYS IN THE FIELD. LEGEND: ● INCLUDED, ○ PARTIALLY INCLUDED, □ NOT INCLUDED.

Year	Reference	Literature Review on SSI	Literature Review on Other Applications	Threats & Mitigation	Available Implementations	Regulations, Projects & Organizations	Challenges & Future Directions
2021	Cucko et al. [13]	○	○	○	○	○	●
2021	Soltani et al. [14]	●	●	○	●	●	○
2022	Bai et al. [15]	○	○	○	○	○	●
2022	Schardong et al. [16]	●	○	○	○	○	●
2023	Ernstberger et al. [17]	○	○	●	●	○	●
2024	Krul et al. [18]	●	○	●	●	○	●
2024	Tan et al. [19]	○	●	○	○	●	○
2024	Satybaldy et al. [20]	○	●	○	●	○	●
Now	Our Survey	●	●	●	●	●	●

mental achievement of SSI is the ability for users to present their trusted credentials to a third party without needing an intermediary. This process is enabled through the ownership and control of Decentralized Identifiers (DIDs) [11], which define a globally unique and cryptographic identifier scheme. Each DID is associated with a DID Document, containing publicly available information (e.g., public keys), stored on shared and verifiable data sources such as Distributed Ledger Technologies (DLTs). By presenting a DID, an individual can obtain Verifiable Credentials (VCs) [12]. These VCs include claims regarding the DID that can be verified by an external party without requiring direct engagement with the VC issuer. For example, an individual applying for a job online could present a digitally signed credential from their university, attesting to their acquisition of a bachelor's degree and residency in the relevant country in which they are applying.

Consequently, such technologies can play a key role in establishing trust and secure communications among peers through digital identities [21], encompassing both human and non-human entities such as IoT devices. DIDs and VCs have been proposed as valuable solutions to enhance privacy and security in several application domains (e.g., smart transportation and smart healthcare). These standards can be extended to anyone and anything, including cloud, edge, and IoT re-

sources. Notably, numerous implementations supporting these technologies have recently been developed and made available by different organizations, including major companies in the industry, such as Microsoft. Additionally, government institutions worldwide have been actively working to promote the widespread adoption of DIDs and VCs. For instance, in May 2024, the European Union introduced Regulation 2024/1183 [22], establishing the European Digital Identity Framework. This initiative seeks to provide European citizens with secure access to online and offline public and private services throughout Europe via an SSI system, reflecting a significant stride toward the advancement of digital identity solutions.

A. Comparison with Related Surveys

Interest in DIDs and VCs has rapidly grown worldwide, drawing significant attention from academia, industry, governments, and standardization bodies. This trend is fueled by the increasing number of research papers and initiatives emerging in recent years. However, most existing surveys primarily focus on the role of DIDs and VCs within SSI ecosystems, often overlooking their wider applications. In contrast, this survey aims to provide a comprehensive overview of the use of these technologies. Table I briefly summarizes key

contributions of relevant surveys in the field, while Table II presents a comparative analysis, highlighting their scope and focus. INCLUDED (●) means that the paper thoroughly covers the topic in question, while PARTIALLY INCLUDED (◐) indicates that the paper covers the topic to some extent but not in full depth.

Literature Review on SSI and Other Applications. This survey offers a comprehensive overview of how DIDs and VCs are employed across various areas, such as smart transportation and industry. Other surveys primarily focus on SSI [16] or narrow their scope to subtopics [14], [18], [20]. Beyond reviewing papers on SSI, Soltani et al. [14] also consider a few other application domains, such as healthcare and IoT. Tan et al. [19] cover a broader range of fields but their literature review does not emphasize how DIDs and VCs are used in these domains.

Threats & Mitigation. Threat and mitigation strategies are often overlooked in existing literature. Our survey is one of the few to identify threats related to DIDs and VCs, while also proposing potential mitigation strategies. Similar to our work, Krul et al. [18] discuss threats and mitigation in SSI systems, while Ernstberger et al. [17] present a concise threat model for SSI.

Available Implementations. This survey provides practical guidance for developers by identifying the most suitable solutions for their needs, unlike other works that primarily report frameworks and some of their features. Krul et al. [18] list the main industrial solutions and how they support identification, credential exchange, and some security and privacy properties. Ernstberger et al. [17] offer tabular comparisons of supported functionalities, while other studies provide a brief overview of a few frameworks [14], [20].

Regulations, Projects & Organizations. A key contribution of our work is an extensive review of regulations, projects, and organizations emerging worldwide. Only Tan et al. [19] and Soltani et al. [14] conduct similar research; however, their studies are limited to the main initiatives in Europe and the United States.

Challenges & Future Directions. While almost all related works discuss challenges and future directions, most either address them briefly or focus on sub-fields. For instance, Ernstberger et al. [17] and Krul et al. [18] focus on privacy and security challenges. Our survey identifies a wide range of challenges and future research directions specific to DIDs and VCs. Satybaldy et al. [20] provide the most comprehensive analysis of SSI challenges but they only present a few research directions.

B. Contributions

Related surveys primarily focus on how DIDs and VCs have been employed in SSI systems, often overlooking critical areas such as security, practical implementations, alternative applications, and regulations. This survey aims to bridge these gaps by providing an in-depth examination of DIDs and VCs. It covers a wide range of topics, including foundational concepts, security threats, potential mitigation, major available

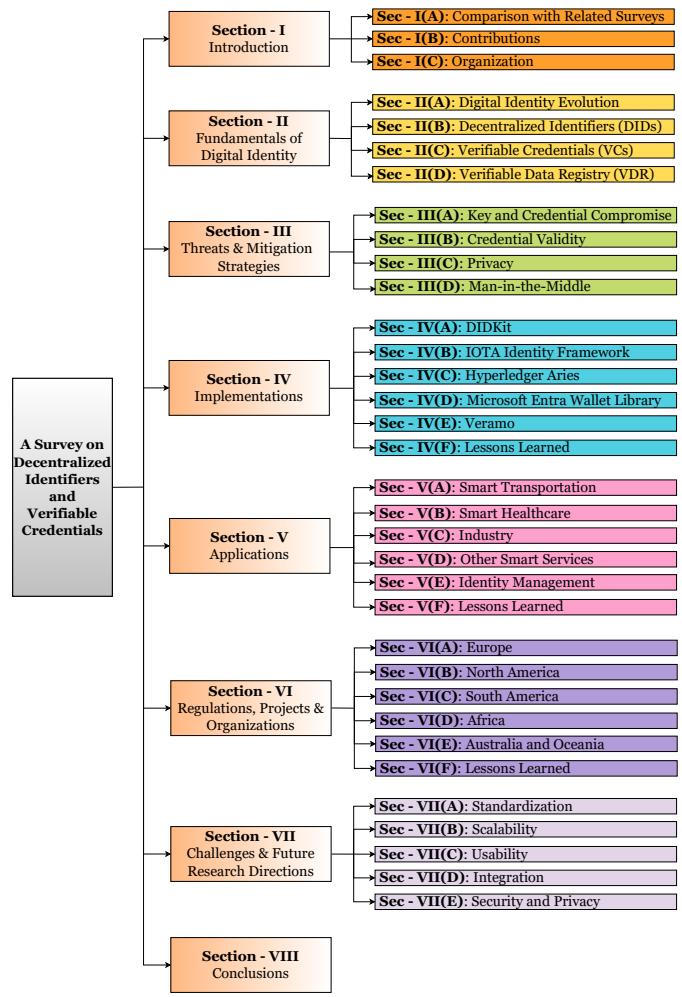


Fig. 1. Illustrative organization of the survey.

implementations, application domains, as well as challenges and emerging research directions. We believe that this paper offers a comprehensive resource for readers aiming to gain thorough understanding of these emerging technologies. The key contributions of our work can be summarized as follows:

- We identify the key threats associated with DIDs and VCs and propose potential mitigation strategies to address them.
- We conduct a comparative analysis of the main commercial implementations available, aiding developers in making informed decisions tailored for their specific needs.
- We review how DIDs and VCs have been employed in research papers across diverse applications, which goes beyond SSI systems.
- We report and discuss a wide array of global initiatives, regulations, and projects that have emerged, providing valuable insights into the potential of these technologies and how they have been adopted worldwide.
- We identify and highlight critical challenges that are specific to DIDs and VCs. Moreover, we point out under-explored areas that warrant further investigation, outlining promising research directions.

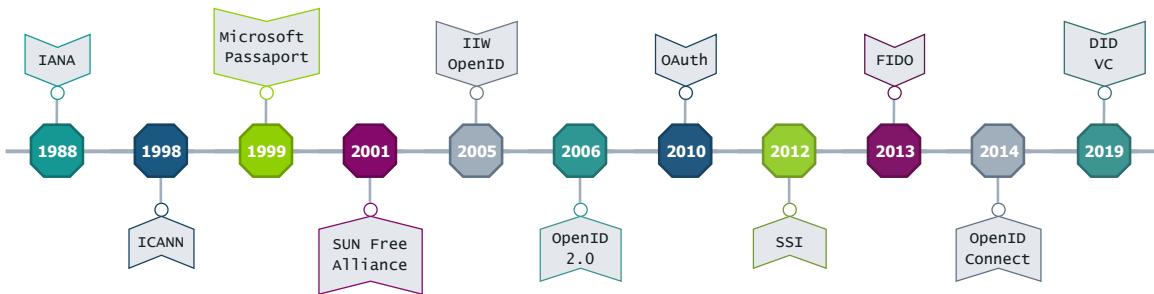


Fig. 2. Timeline of digital identity evolution.

C. Organization

Figure 1 illustrates the structure of this survey, the remainder of this paper is organized as follows. Section II provides the foundation of digital identities by outlining their evolution over time, with particular focus on DIDs and VCs. Section III identifies key security threats associated with DIDs and VCs. It also discusses potential mitigation strategies, which are crucial for ensuring the secure adoption of these technologies. Section IV shifts from theoretical aspects to practical considerations, exploring the spectrum of main available implementations. This section helps developers in selecting the most suitable solution based on their specific needs. Section V links the technical and practical aspects by reviewing the various applications of DIDs and VCs across different research domains, demonstrating their real-world impact and versatility. Section VI examines the broader ecosystem by offering insights into global regulations, projects, and organizations. Section VII identifies existing challenges that hinder the widespread adoption of these technologies and highlights opportunities for future research, bridging current limitations with potential advancements. Finally, Section VIII summarizes the key insights from the survey and provides concluding remarks. Table III reports a list of abbreviations frequently used throughout the paper.

II. FUNDAMENTALS OF DIGITAL IDENTITY

This section provides an overview of the development of digital identities, with a focus on the standards and technologies that enable SSI systems.

A. Digital Identity Evolution

The evolution of digital identity has undergone many eras, which have gradually shifted digital identification from centralized to decentralized identity models [23]. Figure 2 depicts this timeline evolution.

Centralized Identity. In centralized identity systems, identities are managed by a central authority [24]. One of the earliest forms of digital identity dates back to 1988 when the Internet Assigned Numbers Authority (IANA) was responsible for determining the validity of IP addresses. Later, the scientific community witnessed the emergence of organizations such as the Internet Corporation for Assigned Names and Numbers (ICANN), which arbitrates the validity of domain names.

TABLE III
LIST OF THE ACRONYMS FREQUENTLY USED IN THIS ARTICLE.

Acronym	Description
ABAC	Attribute-based Access Control
CID	Content Identifier
DAG	Direct Acyclic Graph
DID	Decentralized Identifier
DHS	Department of Homeland Security
DIACC	Digital Identity and Authentication Council of Canada
DLT	Distributed Ledger Technology
DT	Digital Twin
eIDAS	Electronic Identification and Trust Services
EBSI	European Blockchain Services Infrastructure
EU	European Union
EUDIW	European Digital Wallet
EV	Electric Vehicle
FL	Federated Learning
FIDO	Fast IDentity Online
5G	5th Generation Mobile Networks
GDPR	General Data Protection Regulation
IIoT	Industrial Internet of Things
IoMT	Internet of Medical Things
IoT	Internet of Things
IoV	Internet of Vehicles
IPFS	Internet Planetary File System
ML	Machine Learning
OAuth	Open Authorization
OEM	Original Equipment Manufacturer
SSI	Self-Sovereign Identity
SSO	Single-Sign On
U.S.	United States
VC	Verifiable Credential
VDR	Verifiable Data Registry
VIN	Vehicle Identification Number
V2X	Vehicle-to-anything
V2V	Vehicle-to-vehicle
VP	Verifiable Presentation
W3C	World Wide Web Consortium
ZKP	Zero-Knowledge Proof

Centralized identity management systems rely on usernames and passwords for authentication, which raises several concerns [25], as users often prioritize simplicity over security when choosing their credentials. This makes them vulnerable to attacks such as dictionary or phishing attacks. Moreover, individuals usually have as many identities as the number of services, resulting in a fragmented identity landscape.

Centralized models suffer from a single point of failure and expose user-related information to potential risks, whether from centralized authorities or through data breaches [26], [27]. Consequently, this identity model also poses challenges for service providers [28], requiring substantial investments to securely store, preserve, and safeguard user data in compliance

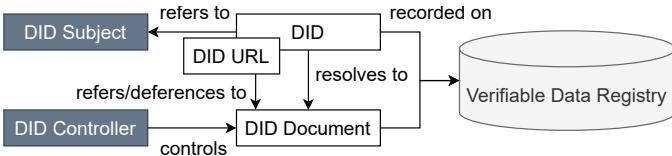


Fig. 3. Overview of a DID-based architecture and the relationship of the main components.

with existing regulations.

Federated Identity. Federated identity represents the second era of digital identification, addressing some of the challenges associated with centralized identification. It allows users to utilize the same identity across multiple sites and applications [29]. By logging in once, users can access various resources without creating separate accounts for each system. This approach relies on trusted relationships between different parties to ensure secure authentication and authorization. Indeed, federations are achieved by distributing identification and verification components across systems or by mutually accepting shared standards between them.

One of the pioneers in proposing federated identity was Microsoft with its Passport program, which allowed users to access different websites with a single login. In 2001, Sun Microsystems formed the Liberty Alliance to develop open standards for federated identity and identity-based web services. Today, major companies like Google and Meta offer Single Sign-On (SSO) support [30]. A typical federated scenario involves a user authenticating through an identity provider (e.g., Google or Meta identity providers) and then gaining access to other applications on its behalf.

While federated models reduce identity fragmentation, they still pose privacy concerns. Despite a decrease in the number of centralized entities involved, users must trust identity providers, which remain centralized, offering limited control over user data. Furthermore, federated identity relies on mutual recognition between two or more parties, which may be increasingly complex at scale [31].

User-centric Identity. The demand for greater control over personal data has given rise to user-centric identity. This model empowers individuals to manage their identities independently or across multiple authorities without relying on centralized federations [32], [33]. Users retain autonomy and must explicitly grant consent before sharing or modifying their data, enhancing privacy and security.

In 2005, the Identity Commons, an influential American organization with a mission to support, facilitate, and promote the creation of an open identity layer for the Internet, played a pivotal role in advocating for the Internet Identity Workshop (IIW). The IIW places users at the core of identity management, aiming to empower individuals in shaping their online identities. This led to numerous projects embodying user-centric principles, including OpenID, OpenID 2.0, OpenID Connect (OIDC), Open Authorization (OAuth), and Fast IDentity Online (FIDO) [33]–[35]. User-centric approaches enable individuals to control their data through various authenticators (e.g., JSON Web Tokens) and certificates issued by different



Fig. 4. An example of a DID and its DID Document.

service providers, all securely stored on their devices.

Despite the notable progress, user-centric identity systems still depend on trust relationships with service providers and authorities, requiring users to trust these entities to handle their information responsibly and not misuse it [36].

Self-Sovereign Identity. SSI represents the last era in the long and evolving journey of digital identity evolution. Introduced in 2012, this concept marks a significant advancement over user-centric identity systems [37].

In contrast to conventional identity management systems, where the service provider controls the identity model, SSI places the individual at the core. Users are granted full control over their identities, enabling them to decide when, if, and how they wish to disclose or modify their data. SSI relies on decentralized infrastructure and cutting-edge technologies such as DLTs, DIDs, and VCs. By leveraging DLTs like *blockchain*, SSI eliminates the need for central authorities [38], fostering a trustless environment where users can interact with services and applications without exposing their sensitive information to a single entity [39]. This decentralized architecture ensures that data is cryptographically secured and verifiable, delivering transparency and immutability for identity management.

In an SSI ecosystem, individuals are uniquely identified by DID, linked to a key pair controlled by the user. The public key bound to the identifier is usually shared on a DLT, allowing users to verify identities independently [10]. Users prove attributes or claims through VCs, which can be cryptographically verified by any other parties without interacting with the issuing centralized authority. These credentials are typically transmitted off-chain due to privacy considerations, with verification depending on publicly available information associated with the identifier and credential issuer.

B. Decentralized Identifiers (DIDs)

DIDs have emerged as a groundbreaking digital identifier widely embraced within decentralized identity systems. They were formalized and standardized by the World Wide Web Consortium (W3C) [40] after substantial collaborative efforts from 2017 to 2019, culminating in the publication of the DID specification as an official W3C Recommendation. Figure 3 provides an overview of the major components of a DID-based architecture.

Architecture. A DID uniquely identifies a DID Subject, which can be either a human or non-human entity. It consists of three essential components: the Uniform Resource Identifier, the identifier for the specific DID method, and the method-specific identifier for the DID. The DID method specifies the processes for creating, resolving, updating, and deactivating DIDs and DID Documents. The DID URL extends a basic DID by including additional URI components like path, query, and fragment, enabling precise resource location within a DID Document or an external resource.

Each DID resolves to a DID Document, a machine-readable JSON-LD document containing information about the DID Subject, such as cryptographic public keys, service endpoints, authentication parameters, timestamps, and additional metadata. DIDs are consistent and permanent, offering reliable identification even as individuals switch service providers or platforms. Figure 4 shows an example of DID and its corresponding DID Document.

DIDs are designed to eliminate reliance on centralized identity providers, fostering the adoption of SSI systems. Users have control and ownership over their DIDs, which can be created and managed by themselves. An entity can prove the ownership of a DID by leveraging the private key corresponding to the public key in the DID document. The verifier can access DID Document, which is publicly available through a Verifiable Data Registry (VDR).

The DID Controller is the entity authorized to modify the DID Document. A DID might have multiple controllers or may coincide with the DID Subject, aligning with the principles of the SSI paradigm. DIDs are resolved through a universal resolver [41] that supports multiple DID systems. A DID system needs to implement a DID adapter to be compatible with the universal resolver, functioning as an interface between system-specific DID methods and the universal resolver.

Types of DIDs. The DID specification [42] introduces three types of DIDs:

- Anywise DIDs can be utilized with an unspecified number of parties, typically strangers. They allow broad usage without limiting the number of relationships that can be established.
- Pairwise DIDs are only known by their subject and one other party, such as a service provider. Pairwise DIDs address privacy concerns by ensuring that each relationship has a unique DID, minimizing the risk of correlation between different interactions.
- N-wise DIDs are designed to be known by strictly N parties, including the subject. They encompass pairwise DIDs as a special case when N equals 2.

Communication Protocols. The growing interest in DID has also led to the development of DID-based communication protocols [43], [44], enabling private and secure communication between two or more SSI entities. These protocols rely on DIDs and facilitate mutual authentication between the participating parties.

The DID Auth protocol allows an identity owner to use their client application, such as a mobile device or browser, to prove their control over a DID to a service provider. This

```
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://www.w3.org/2018/credentials/examples/v1"
  ],
  "id": "http://example.edu/credentials/1872",
  "type": ["VerifiableCredential", "AlumniCredential"],
  "issuer": "https://example.edu/issuers/565049",
  "issuanceDate": "2010-01-01T19:23:24Z",
  "credentialSubject": {
    "id": "did:example:ebfeb1f712ebc6f1c276e12ec21",
    "alumniOf": {
      "id": "did:example:c276e12ec21ebfeb1f712ebc6f1",
      "name": [
        {
          "value": "Example University",
          "lang": "en"
        },
        {
          "value": "Esempio di Università",
          "lang": "it"
        }
      ]
    },
    "proof": {
      "type": "RsaSignature2018",
      "created": "2017-06-18T21:19:10Z",
      "proofPurpose": "assertionMethod",
      "verificationMethod":
      "https://example.edu/issuers/565049#key-1",
      "jws": "eyJhbGciOiJSUzI1NiIsImI2NCI6ZmFsc2UsImNyaXQiOlsiYjY0... "
    }
  }
}
```

Fig. 5. Example of a VC allowing alumni of Example University to receive discounts on season tickets for sporting events.

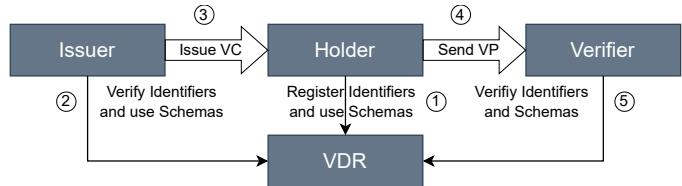


Fig. 6. Overview of VC main actors.

protocol utilizes a challenge-response cycle that can be customized based on the specific circumstance, potentially replacing traditional forms authentication methods like usernames and passwords, establishing an authenticated communication channel between the identity owner and the service provider.

C. Verifiable Credentials (VCs)

VC is a specification developed by the W3C to create an interoperable data structure capable of representing claims (e.g., properties or attributes) that are cryptographically verifiable and tamper-proof. VC s are designed to seamlessly operate across different platforms and applications. Individuals can store VC s in their digital wallet and carry them anywhere while ensuring they remain verifiable. This flexibility and convenience allow users to present their credentials efficiently. Figure 5 shows an example of VC that enables all alumni of "Example University" to receive a discount on season tickets to sporting events.

Main Actors. In the VC ecosystem, a holder refers to an entity exercising control over one or more VC s. These credentials are issued by trusted entities such as government agencies or

banks. A verifier is an entity, such as an e-commerce website, that requires valid credentials to offer a service. Figure 6 illustrates the key roles within the ecosystem of VCs.

To facilitate the creation and verification of identifiers, keys, verifiable credentials schema, and other relevant data essential for using VCs, are shared through a VDR, which acts as a mediator within the ecosystem. Since credentials often contain sensitive information, they are typically shared off-chain instead of being stored on a VDR or a centralized system. This approach minimizes the risk of data exposure by keeping sensitive information out of public or easily accessible systems, ensuring greater privacy and security for the user.

Structure of VCs. Similar to DIDs, VCs also consist of several elements, including the Subject URI, the URI of the issuer responsible for the claims, and URIs that uniquely identify the credential. The Subject URI is used to retrieve the subject's public key, ensuring verification of the credential's ownership. Meanwhile, the issuer URI is essential for obtaining their public key and verifying that the credential originates from a trusted entity. Notably, the URI can also take the form of a DID.

Furthermore, VCs include claim expiration conditions and cryptographic signatures, ensuring that the credential validity is maintained over time and that the integrity of the information is secured through cryptographic verification.

Verifiable Presentation. The W3C Verifiable Credentials Working Group has also defined the concept of Verifiable Presentations (VPs), which specify the methods for signing and presenting VCs by the holder. VCs or VPs can be described using JSON-LD, JSON, or JSON Web Token formats. Figure 7 shows a VP obtained from the VC of the previous example. The standard related to expressing verifiable information on the Web has been published to provide a regulation specification for expressing credentials on the Internet ensuring that they are machine-verifiable, respect privacy, and, most importantly, are cryptographically secure.

Selective Disclosure. To grant individuals full control over their data, VCs allow selectively disclosing a subset of the information contained with them. Over the years, various methods for selective disclosure have been developed [45], [46]. They are usually categorized into mono claims, hashed values, Zero-Knowledge Proofs (ZKP), and selective disclosure signatures. The current state-of-the-art solution is SD-JWT [47], which enhances privacy by replacing plaintext claims with digests of their salted values. When the holder discloses specific information, they share the original claim and the corresponding salt.

D. Verifiable Data Registry (VDR)

In the context of DIDs and VCs, a VDR plays a crucial role in creating, managing, and verifying identifiers, keys, credential schema, and other relevant data required to utilize these decentralized identity technologies [48].

Role of VDR in SSI. A VDR acts as a trusted intermediary within the ecosystem of DIDs and VCs, serving as a repository or database that stores and provides access to

```
{
  "@context": [
    "https://www.w3.org/2018/credentials/v1",
    "https://www.w3.org/2018/credentials/examples/v1"
  ],
  "type": "VerifiablePresentation",
  "verifiableCredential": [
    {
      "@context": [
        "https://www.w3.org/2018/credentials/v1",
        "https://www.w3.org/2018/credentials/examples/v1"
      ],
      "id": "http://example.edu/credentials/1872",
      "type": ["VerifiableCredential", "AlumniCredential"],
      "issuer": "https://example.edu/issuers/565049",
      "issuanceDate": "2010-01-01T19:23:24Z",
      "credentialSubject": {
        "id": "did:example:ebfeb1f712ebc6f1c276e12ec21",
        "alumniOf": {
          "id": "did:example:c276e12ec21ebfeb1f712ebc6f1",
          "name": [{"value": "Example University", "lang": "en"}, {"value": "Exemple d'Université", "lang": "fr"}]
        }
      },
      "proof": {
        "type": "RsaSignature2018",
        "created": "2017-06-18T21:19:10Z",
        "proofPurpose": "assertionMethod",
        "verificationMethod": "https://example.edu/issuers/565049#key-1",
        "jws": "eyJhbGciOiJSUzI1NiIiSmI2NCI6ZmFsc2UsImNyaXQiolsiYjY0..."
      }
    ],
    "proof": {
      "type": "RsaSignature2018",
      "created": "2018-09-14T21:19:10Z",
      "proofPurpose": "authentication",
      "verificationMethod": "did:example:ebfeb1f712ebc6f1c276e12ec21#keys-1",
      "challenge": "1f44d55f-f161-4938-a659-f8026467f126",
      "domain": "4jt78h47fh47",
      "jws": "eyJhbGciOiJSUzI1NiIiSmI2NCI6ZmFsc2UsImNyaXQiolsiYjY0..."
    }
  ]
}
```

Fig. 7. Example of a VP derived from the VC for alumni of Example University.

essential information. This includes DID Documents, which contain details such as cryptographic public keys, service endpoints, authentication parameters, timestamps, and metadata. The VDR ensures the availability and accessibility of these documents to support the resolution and verification processes. When verifiers need to verify a DID or a VC, they retrieve the relevant information from the VDR. By accessing the public information stored in the registry, they can validate the authenticity, integrity, and validity of the DIDs and VCs involved in the verification process, thereby establishing trust and confidence in the decentralized identity ecosystem.

The VDR also manages and maintains the lifecycle of DIDs and VCs. It facilitates the creation, registration, and revocation of DIDs and VCs, acting as a centralized point of control or coordination. For example, when an entity wants to create a new DID or issue a new VC, it interacts with the VDR to ensure proper registration and management of the associated information. Similarly, when a DID or VC needs to be revoked or updated, the VDR can handle the necessary operations to reflect the changes in the system. Additionally, the VDR supports interoperability and standardization within the decentralized identity ecosystem by enforcing consistent data formats, validation rules, and data-sharing protocols. This promotes compatibility and seamless integration across different DID methods, VC issuers, and verifiers.

Implementations. Currently, the W3C's standards do not specify how the VDR should be implemented. Most of the proposed approaches are based on DLTs, with blockchain

standing out as the most popular type of DLT [49]. Blockchain is characterized by interconnected blocks, each referencing to the previous block hash, forming a secure chain [50]. Any tampering would lead to a different hash that can be easily detected. This feature is fundamental for the secure sharing of information such as DID Documents. Additionally, many blockchains also support *smart contracts* [51], which are self-executing programs stored directly on the blockchain and triggered when specific conditions are met. This inherent design ensures fault tolerance, tamper-proofing, and traceability. In the subsequent sections, we will show how these features make smart contracts a valuable technology in various application domains utilizing DIDs and VCs.

Alternative solutions have also emerged. For example, Information-Centric Networking (ICN) is a novel networking paradigm that can be adopted to implement the registry [52]. Users interact with edge nodes to manage DIDs through HTTP APIs, which are then translated into appropriate ICN flows.

III. THREATS & MITIGATION STRATEGIES

Although DIDs and VCs offer significant security and privacy benefits, they are not without vulnerabilities. This section outlines the major threats associated with these technologies and presents potential strategies for mitigation.

A. Key and Credential Compromise

Threat 1: An adversary may perform various attacks, such as phishing, malware, or direct key theft, to compromise the private key associated with a DID or gain unauthorized access to credentials, impersonating the legitimate identity owner.

Mitigation: Mitigating the risks of key and credential compromise requires a multi-faceted approach. Below are some effective strategies:

- **Key Rotation:** Regularly rotating keys and revoking old ones minimizes the damage caused by a potential compromise.
- **Multi-Factor Authentication (MFA):** Implementing MFA enhances the security of wallet access by protecting keys and credentials. MFA can also require the presentation of the same credential from multiple devices, ensuring that compromising a single wallet does not allow the adversary to use the credential as their own.
- **Hardware Security Modules (HSMs):** Storing private keys in secure hardware modules protects them from unauthorized access.
- **Trusted Third Party Key Recovery:** Keys can be securely backed up and recovered through trusted third parties [53], using escrow services to safeguard against key loss.

Threat 2: A malicious user may collude with others or steal a valid credential from a legitimate user, presenting it to a verifier and acting on behalf of the holder.

Mitigation: This threat can be mitigated by associating the VC and their presentation with the identity owner, preventing illegitimate transfers. The holder identifier, such as a DID, is included in the VC, whose immutability prevents any alteration. To prove ownership over the credential, the presenter

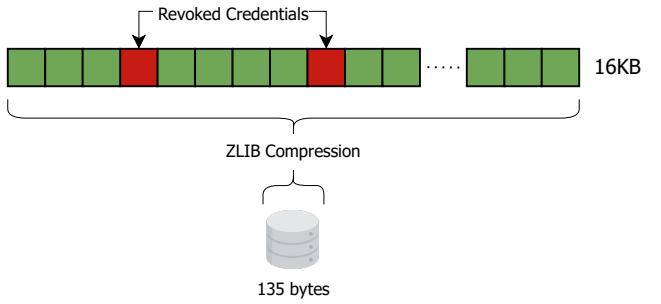


Fig. 8. Revocation List 2020.

must demonstrate knowledge of the identity owner's private key, which is only known by the holder.

Threat 3: An attacker may attempt to gain access to a service by forging a legitimate VC or presenting a credential issued by an entity that lacks the authority to issue VCs.

Mitigation: Credentials must be digitally signed by the issuer, preventing adversaries from forging VCs as they do not know the issuer's private key. Each credential must include an issuer identifier to ensure that a trusted and recognized authority has certified the presented claims. Additionally, a secure register should be maintained to identify all trustworthy issuers and the claims they are authorized to certify.

B. Credential Validity

Threat 4: Although always verifiable, the validity of VCs can change over time due to loss of privileges or expiration. Consequently, a verifier must verify the validity of a credential before accepting it.

Mitigation: The issuer can specify the validity period within the credential itself, enabling the verifier to check whether the credential is still valid.

However, this approach does not account for scenarios where issuers revoke VCs due to a holder's loss of privileges. This concern can be addressed using revocation mechanisms commonly employed for PKI certificates [54], such as Online Certificate Status Protocol (OCSP) [55] and Certificate Revocation Lists (CRLs) [56]. The W3C also proposed the revocation bitstring "Revocation List 2020" [57], where each bit corresponds to an index contained in the VCs. Figure 8 provides an illustrative overview of Revocation List 2020. When a bit is set to 1, the corresponding VC is revoked; otherwise, it remains valid. Since most credentials are expected to remain valid, long stretches of bits often retain identical values. This property makes the bitstring amenable to compression techniques like ZLIB [58], which can reduce its size. Furthermore, concerns about the size of data structures for managing revocation have inspired novel approaches that minimize storage and network requirements [59].

C. Privacy

Threat 5: A VC may contain more claims than necessary for accessing a specific service. Consequently, a service provider

TABLE IV
COMPARATIVE ANALYSIS OF MAIN IMPLEMENTATIONS OF DIDs AND VCs. **LEGEND:** ↑ HIGH, ≈ MEDIUM, ↓ LOW, - NOT SPECIFIED.

Library	DIDKit	IOTA Identity Framework	Hyperledger Aries	Microsoft Entra Wallet	Veramo
Main Target Platform	Multi-platforms	Multi-platforms/IoT Devices	Multi-platforms	Mobile Applications	Multi-platforms
Programming Language	Rust, C, Java, Android, Python, JavaScript	Rust, Node.js	Python, JavaScript, Go, .NET	Android, iOS	JavaScript
W3C Compliance	✓	✓	✓	✓	✓
Credential Format	JSON-LD/JWT	JWT	JSON-LD	JWT	JSON-LD/JWT
Key & Wallet Management	-	Stronghold	-	Azure Key Vault	-
Verifiable Proof Types	RSA/EdDSA/ECDSA/EIP712/JWS2020	EdDSA/ECDSA	BBS+/EdDSA	EdDSA/ES256K/ECDSA P-256	EdDSA, ECDH, ECDSA
Selective Disclosure	SD-JWT	SD-JWT/ZKSD	SD-JWT	SD-JWT	SD-JWT Through Plugin Interface
Verifiable Data Registry	-	Tangle	Indy Ledger	-	-
Learning Curve	↓	≈	↑	≈	↓
Open Source	✓	✓	✓	✓	✓

might acquire more information than required. Malicious service providers could exploit personal data for financial gain through individual profiling, while honest service providers might inadvertently elevate privacy loss risks.

Mitigation: Individuals should provide only the information needed to access the intended service by removing unnecessary claims from a VC when generating the presentation. This can be achieved through employing selective disclosure [45], [46], which allows presenting only a subset of claims contained in a VC. Selective disclosure techniques enable verifying the authenticity of the revealed claims without accessing the entire credential.

Threat 6: Selective disclosure techniques could still allow service providers to link claims to the same individual across subsequent presentations or collude with other providers [18].

Mitigation: Using Pairwise DIDs can help mitigate this risk by reducing the likelihood of correlation, though it does not entirely prevent linkage across multiple presentations. To further reduce the risk, VCs should avoid including persistent user identifiers, such as DIDs, unless necessary for issuer identification. While *complete unlinkability* might be ideal in some scenarios, it is not always appropriate. For instance, when a credential is used for authentication, the service provider must recognize repeat presentations to prevent Sybil attacks. Linked unlinkability approaches [60] can address this, allowing the identification of repeat presentations while minimizing the risk of correlation across different providers.

Threat 7: The holder of a VC may not have permission to access certain confidential information within the credential, which is intended solely for a verifier.

Mitigation: To protect sensitive information, claims within the VC can be encrypted using a secret key known only to authorized service providers. Additionally, selective disclosure mechanisms can be employed, ensuring only the necessary claims to be revealed. In such cases, the information required to reveal claims is shared exclusively with the service providers, not the holder.

D. Man-in-the-Middle

Threat 8: An attacker could intercept and tamper with the communication between a legitimate user and a service provider, potentially gaining access to the contents of the presentation or altering the transmitted information.

Mitigation: Communications between two parties can be secured by using end-to-end encryption protocols [61], which protect the content from unauthorized access. Additionally, as VCs are signed with the issuer's private key, any modification of their content would be detected.

Threat 9: An adversary may intercept a VP and reuse it to a different verifier, impersonating the legitimate holder and gaining unauthorized access.

Mitigation: Replay attacks can be mitigated by including a nonce or a timestamp in the VP. Verifiers should send a challenge set as the nonce within the credential. To be valid, the VP must include the challenge, ensuring it matches the one provided by the verifier.

IV. IMPLEMENTATIONS

The successful implementation of DIDs and VCs plays a crucial role in the widespread adoption of SSI systems and the development of next-generation services. Developers need efficient frameworks that simplify the use of these technologies while adhering to established standards.

Although initially designed to give individuals greater control over personal data, DIDs and VCs have broader applicability, extending to entities such as cloud, edge, and IoT devices, which often feature different storage and computational capabilities. This heterogeneity demands implementations that are optimized to minimize storage and computational overhead.

The development of DIDs and VCs remains in its early stages, with a relatively small number of available implementations. Nonetheless, our analysis provides developers and stakeholders with valuable insights into the key differences among the main solutions, guiding them in choosing the most suitable option for their specific use cases. Table IV reports the key features of main implementations.

A. DIDKit

DIDKit [62] is a toolkit from SpruceID that provides DID and VC functionalities across various platforms. Its core libraries are implemented in Rust, offering advantages such as memory safety, simpler dependency tree, and compatibility with various platforms, including embedded systems.

While DIDKit SDK supports a wide range of use cases, its bindings for other languages such as C, Java, Android, Python, and JavaScript are implemented as wrappers around

the Rust core. As a result, using these bindings may introduce additional challenges and complexity compared to direct Rust usage. DIDKit supports selective disclosure, implemented through SD-JWT. This library offers the following features:

- 1) It can sign and verify any VC compliant to the W3C standard. DIDKit also includes a ready-to-use HTTP/HTTPS server that accessed via any API interface, including those specified by the W3C standard.
- 2) It supports and translates both of the two major signing systems and proof formats used in VC.
- 3) It can handle, authenticate, validate, register, and deterministically generate many kinds of DIDs compliant with the W3C standard.
- 4) It can also issue and consume authorization tokens based on the Object Capabilities "ZCaps".

B. IOTA Identity Framework

The IOTA Identity framework [63] implements decentralized identity solutions using both a DLT-agnostic approach and dedicated IOTA method specification. It is built on the Tangle, a next-generation DLT tailored for the IoT ecosystem. The IOTA Identity Framework enables the creation of new digital identities for any entity, including IoT devices, at any time. These functionalities are offered in Rust and Node.js via Web Assembly (WASM), making it versatile across various environments.

When using IOTA Identity, the verifier can confirm the issuer's identity through their public key on the Tangle, while the holder provides proof of ownership over their DID. IOTA Identity also supports selective disclosure mechanisms following IETF standards, including both SD-JWT and Zero-Knowledge Selective Disclosure (ZKSD).

One of the standout features of the IOTA identity framework is its integration with the IOTA ledger, a Direct Acyclic Graph (DAG), which provides unique benefits:

- *Feeless*: Unlike traditional blockchains, IOTA has no miners or validators. Messages, including DID Documents, can be stored without incurring transaction fees. This feeless nature allows the deployment of SSI applications directly on the main network at no cost, promoting global accessibility and inclusivity.
- *Ease-of-use*: IOTA Identity is accessible without any cryptocurrency token. It also provides simple APIs that allow standardized and flexible functionalities. Additionally, the framework includes a stronghold to securely manage secrets.
- *General Purpose DLT*: IOTA is a general-purpose DLT, enabling SSI integration with other features such as payments, data streams, smart contracts, and access control.

C. Hyperledger Aries

Hyperledger Aries [64] is an open-source project within Hyperledger ecosystem that offers a complete suite of tools and libraries for building decentralized identity applications. It supports DIDs and VCs, ensuring their secure storage and presentation while maximizing privacy preservation. Aries is

designed to be highly flexible, supporting multiple protocols, various credential types, ledgers, and registries, as well as providing interoperability tools across different identity systems.

Developers can create novel applications by integrating application-specific code that controls the Aries agent. Currently, there are several Aries general-purpose agents, with others under active development:

- *Aries Cloud Agent - Python*: Suitable for all non-mobile applications and has production deployments. It runs alongside a controller and communicates using an HTTP interface. The controller can be implemented using any language and the agent embeds Indy-SDK.
- *Aries Framework - .NET*: Designed for building mobile and server-side agents, this framework is also used in production environments. Similar to the Python-based agent, the controller can be written in any language, and the framework can be embedded as a library. It also includes the Indy-SDK.
- *Aries Static Agent - Python*: A configurable agent that does not use persistent storage, making it lightweight and straightforward for specific use cases.

Despite its potential, the development resources available for Aries agents can be somewhat limited. Hyperledger provides an online course for developers, which is offered at certain times throughout the year.

In terms of security and performance, Hyperledger Aries stands out as one of the most robust platforms for decentralized identity systems. However, for testing purposes or certification in process-heavy environments, Aries may not be the optimal choice due to its architectural complexity and the steep learning curve required to effectively use and deploy its agents.

D. Microsoft Entra Wallet Library

Microsoft has been actively developing the Microsoft Entra Wallet Library [65], a novel library to manage DIDs and VCs on iOS and Android platforms. It enables mobile applications to integrate with the Microsoft Entra Verified ID platform, supporting the issuance and presentation of VCs in compliance with various industry standards, including OpenID Connect, Presentation Exchange, and VCs.

By default, Microsoft Entra Wallet Library uses distinct DIDs for each interaction with relying parties, ensuring privacy protection by preventing the correlation of user actions. Moreover, the library automates the retrieval of exchanged VCs directly from the original issuer, streamlining the process and maintaining the integrity of the credentials. The library supports the following requirements, providing flexibility for verifiers and issuers:

- *GroupRequirement*: Allows verifiers or issuers to request multiple requirements simultaneously, aggregating them into a list.
- *VerifiedIdRequirement*: Enables a verifier or issuer to request a specific VerifiedId, which serves as the primary credential for the user.
- *SelfAttestedClaimRequirement*: Allows an issuer to request self-attested claim, which are simple string values provided by the user.

- *PinRequirement*: Enables an issuer to require a PIN from the user as part of verification or issuance process.
- *AccessTokenRequirement*: Allows an issuer to request an Access Token. This typically involves the use of an external library.
- *IdTokenRequirement*: Permits an issuer to request an Identity Token (Id Token). If the token is not included in the request, it must be obtained through an external library.

Despite its potential, Microsoft Entra Wallet Library has some limitations. To access developer resources, users must register for the Microsoft 365 Developer Program and provide personal information. In terms of usability, the Microsoft Entra Wallet is primarily optimized for mobile devices, limiting its broader use cases. However, it remains a promising solution for IT admins managing access to apps and resources and for app developers seeking to implement SSO functionalities using existing user credentials.

E. Veramo

Veramo [66] is a JavaScript Framework designed to simplify the use of DIDs and VCs. Its flexibility and modularity make it adaptable for a wide range of use cases and workflows. At the core of Veramo is the Veramo Agent, which leverages a plugin-driven architecture to provide scalability and integration with emerging standards in the verifiable data ecosystem.

The Veramo Agent is responsible for creating identifiers, resolving identifiers, credential issuance, credential revocation, credential exchange, and secret application hot sauce. These functionalities are implemented via plugins, which expand the agents capabilities and ensure adaptability. Additionally, Veramo is multi-platform, running seamlessly across Node.js, browsers, and React Native, making it suitable for a wide array of development environments. Veramo further enhances usability with a Command Line Interface (CLI), allowing developers to quickly create DIDs and VCs or run a local cloud agent directly from the terminal. This streamlines both the development and testing processes, making it an attractive tool for decentralized identity solutions.

Moreover, Veramo supports selective disclosure through a dedicated plugin, enabling holders to selectively reveal specific claims within a VC, thus protecting sensitive information during credential verification. While this feature is still in its beta phase, it demonstrates Veramo's commitment to offering robust privacy features aligned with emerging IETF standards.

F. Lessons Learned

The exploration of the most popular implementations and frameworks highlights their adherence to the W3C standard and open-source nature - two key factors favoring the widespread adoption of DIDs and VCs. In particular, this adherence ensures seamless interoperability across different systems, which is crucial for the successful integration of these identity technologies. Reviewing implementations shows that some are more generic and web-centric (i.e., DIDKit, Hyperledger Aries, and Veramo), while others are tailored for specific application domains. Consequently, developers

must choose a framework that aligns with their needs and application scenarios.

Among the existing implementations, DIDKit offers notable flexibility by supporting a variety of popular programming languages. Its inclusion of a ready-to-deploy HTTP/HTTPS server makes it particularly valuable for developers approaching these standards for the first time. Similarly, Veramo is designed to simplify the creation of decentralized identity applications; however, its limitation to JavaScript may influence developer's decisions. While Hyperledger Aries provides a robust solution, the initial learning curve may pose challenges, especially for developers unfamiliar with the Hyperledger ecosystem.

As outlined throughout this survey, the scope of DIDs and VCs extends beyond only individuals and is potentially applicable to any entity, including machines. In this context, the IOTA Identity framework emerges as a natural and promising solution to enable the adoption of these technologies in real-world scenarios, involving both humans and IoT devices. IOTA's underlying distributed ledger not only facilitates the use of these technologies but also inherently supports a VDR, eliminating the need for configuring an additional DLT to disseminate publicly available information like DID Documents.

For developers focusing on mobile-centric solutions, the Microsoft Entra Wallet Library stands out as it is specifically designed for managing DIDs and VCs on various mobile devices (e.g., smartphones and smartwatches) running iOS and Android. This implementation empowers developers to provide end-users with comprehensive control over their data through their preferred mobile devices. The active involvement of major technology companies is crucial in advancing these technologies and delivering solutions seamlessly integrated into the modern digital landscape.

V. APPLICATIONS

In this section, we provide an in-depth analysis of DIDs and VCs, exploring their application across various domains. The versatility of these technologies becomes evident through their use across a wide spectrum of fields, ranging from smart transportation to smart healthcare.

We selected the application domains based on the maturity of each field in adopting digital identity solutions, the potential for significant real-world impact using DIDs and VCs, and the existence of a robust body of research supporting these developments. Figure 9 visually categorizes these application areas, summarizing key findings from state-of-the-art research that leverage the capabilities of DIDs and VCs.

A. Smart Transportation

Recent technological advancements have significantly contributed to the development of modern intelligent transportation systems (ITS) [79], which impact various aspects of our lives. Smart transportation involves integrating communication technologies with vehicular services in transportation systems [80]. In particular, Vehicle-to-Vehicle (V2V) communications have opened up for novel applications aiming to improve road traffic efficiency and road safety [81]. For example, vehicles

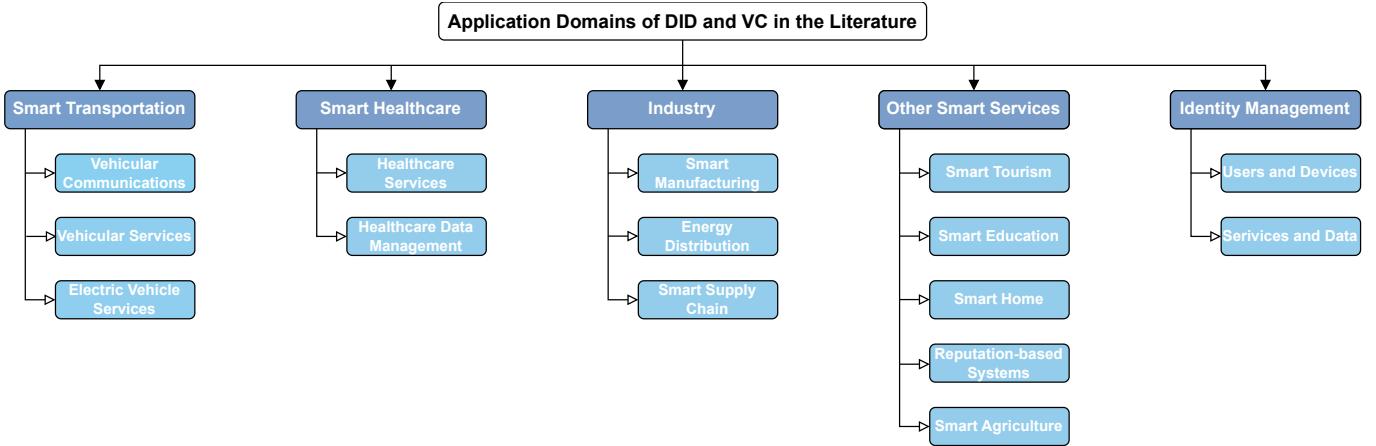


Fig. 9. Application domains of DID and VC in the existing literature.

TABLE V
TAXONOMY OF SMART TRANSPORTATION APPLICATIONS.

Work	Use Case	Main Contributions
[67]	V2X Protocol	A blockchain-based decentralized vehicle-to-anything protocol that enables vehicles to authenticate and validate their information.
[68]	Secure Data Provenance	A protocol that leverages VC to achieve secure data provenance in IoVs.
[69]	V2X Protocol	A decentralized key management system based on blockchain and SSI principles.
[70]	V2X Reputation System	A V2X reputation system that allows transferring reputation to preserve privacy.
[71]	Vehicle Authentication	A secure registration and authentication mechanism for decentralized VANETs, assisted by double-layer blockchain and DIDs
[72]	Seaport Truck Authentication	A secure, portable, decentralized, and user-controllable identity scheme for truck authentication in seaports.
[73]	Vehicle Rights	A decentralized identity management and vehicle rights delegation system.
[74]	Vehicle Data	A mechanism for establishing vehicle data provenance in real-time.
[75]	Vehicle Identity	A cost-effective implementation of the MOBI standard for vehicle identity.
[76]	Energy Trading	A blockchain-based energy trading scheme for electric vehicle-to-vehicle interactions.
[77]	EV Charging	A protocol for EV charging authentication and authorization that can be integrated into ISO 15118.
[78]	Customer Privacy	A user-empowered privacy-preserving authentication protocol for EV charging.

can exchange critical data regarding road conditions or accidents. However, a key challenge in V2V communications is the lack of trust between vehicles, as they typically do not have prior relationships and rely on centralized network authorities. DIDs and VCs offer promising solutions for establishing a more secure and decentralized ITS ecosystem. Table V provides a summary of the relevant literature in this area.

Vehicular Communications. In V2V communications, DIDs and VCs ensure integrity, authentication, confidentiality, and privacy without relying on a centralized trusted authority. These technologies, when combined with DLTs, enable promoting decentralized solutions that meet the requirements of ITS applications. This trend has been further endorsed by the MOBI Alliance [82], which introduced a blockchain-based Vehicle IDentification (VID) standard in 2019 [75]. Built on the DID specification, this standard enhances the traditional Vehicle Identification Number (VIN), making it compatible with the blockchain ecosystem. Figure 10 illustrates a high-level architecture of a potential ecosystem based on VID and DLT.

An example of such a protocol is D-V2X [67], a blockchain-based decentralized Vehicle-to-Anything (V2X) protocol that

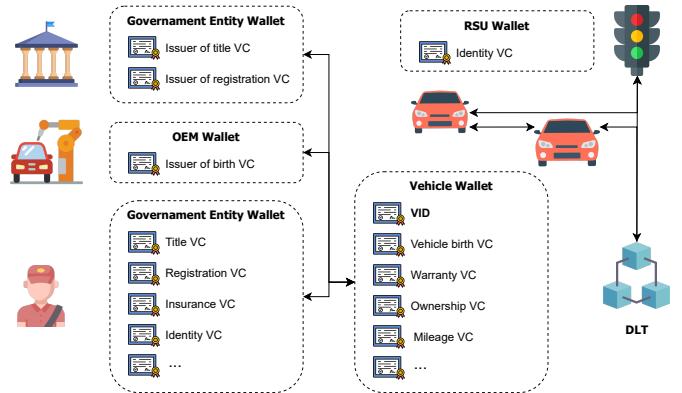


Fig. 10. The DID/VC-enabled smart transportation reference architecture presented by MOBI [10].

eliminates the need for a trusted intermediary. The key element of this system is the decentralized vehicular PKI (D-VPKI), which replaces the traditional VPKI used in V2X communications [83]. To link a VIN to a vehicle using the blockchain, the vehicle first registers a random DID with the D-VPKI. The original equipment manufacturer (OEM)

then issues a VC embedding the VIN and any other relevant data. In a fully decentralized set up, the vehicle acts as both the subject and holder. Whenever the vehicle needs to prove its DID association with its VIN, it provides the VC. To preserve privacy, a vehicle registers multiple DIDs, all linked to the master DID through ZKP-enabled VCs issued by the OEM, which will remove the DIDs post-creation. Alternatively, Secure Multiparty Computation (MPC) can be employed to issue VCs, preventing the OEM from linking the original DID. Vehicles can also use pseudonyms by creating two VPs: one to demonstrate the link between pseudonym and master DID, and another to validate the master DID without revealing it.

In addition, to counter GPS spoofing attacks, a vehicle can obtain a VC from a nearby infrastructure (e.g., a traffic light), certifying its location. Such a concern can also be addressed through secure data provenance protocols [68]. Vehicles register with local Road Side Units (RSU) by presenting a VC attesting to some attributes. RSUs maintain a table for each vehicle, including its attributes and location at a particular time, leveraging basic safety messages. A vehicle that receives claims from another vehicle, interacts with the RSU to check whether the claimed location is correct. Vehicular Decentralized Key Management (VDKMS) [69] is another proposal that leverages DIDs and VCs to achieve secure communication and efficient key management in V2X networks. Similarly to D-V2X, authorized vehicles are provided with a VC that binds the DID to vehicle information, including its VIN.

Privacy-preserving computation is a significant concern in V2X communications. One method to avoid tracking vehicles consists of changing the blockchain address while retaining reputations [70]. This mechanism prevents an external observer from linking new and old addresses. The vehicle locally generates a new address using a secret, derived from the private key of its DID. These addresses form a deterministic chain, allowing reconstruction for auditing or investigation purposes. To transfer reputation, the vehicle generates a "promise" containing the new address, the reputation value, and a random nonce. This information is hashed and sent, along with a ZKP, to a smart contract that verifies the proof, checks the reputation balance, and stores the hash in a Merkle Tree. The old address is then removed from the reputation mapping, and the reputation is released to whoever can prove ownership of the new address.

Vehicular Services. The integration of DIDs and VCs paves the way for novel services in smart transportation, ranging from optimal route planning and access to trucks at seaports to transferring vehicle rights and V2V payments. For instance, BDRA [71] leverages DIDs and a double-layer blockchain for secure registration and authentication. The upper layer comprises all authorized RSUs, while the lower layer includes the RSU and the vehicles within their coverage areas. During registration, each vehicle generates its own DID and submits it to the covering RSU. RSUs collaborate with each other to create a unique VC, granting vehicles access to services, such as optimal route planning or real-time road condition updates.

Furthermore, they enable authenticated communications with other vehicles. When a vehicle receives a message, it authenticates the sender and verifies the sender's DID against the list of users authorized in the lower layer blockchain, ensuring the sender reputation meets a predetermined threshold. The recipient vehicle evaluates the message content, providing feedback to the RSU, which updates its reputation on the blockchain.

In seaports, trucks can be equipped with SSI credentials, such as "vehicle in service", issued by trusted authorities. DIDs and VCs can be used to enhance transportation efficiency where thousands of tons of goods are moved [72]. When a truck performs actions like picking up containers, it must provide the necessary VCs to validate its authorization.

DIDs and VCs also streamline vehicle ownership transfers and service access [73]. A vehicle owner can use pairwise DIDs, private and not shared on the blockchain, to grant temporary access to a service provider for vehicle checks or to a friend borrowing the vehicle.

As connected vehicles and mobility applications increasingly rely on data from diverse sources, ensuring data provenance becomes critical to preventing misuse and manipulation. DIDs can be employed to secure data provenance in an automotive data processing chain, as demonstrated in a use case involving an ML for detecting hazardous driving situations [74]. Here, data provenance is achieved by appending new links - represented by DIDs - within a chain of signed and linked data versions. Each data point is signed by its producer and linked to its previous state, enabling traceability throughout the data lifecycle.

MOBI is actively developing a vehicle identity standard to support blockchain-based use cases such as V2V payments and Vehicle-to-Infrastructure (V2I) payments, automotive insurance, and financing. One practical implementation is the Connected Vehicle Information Network (CVIN) [75], where each vehicle is identified through a CVID ID, a DID-based identifier.

Electric Vehicle Services. In recent years, Electric Vehicle (EVs) have experienced significant growth, driven largely by rising concerns about climate change and sustainability. However, this gradual expansion has not been followed by a corresponding increase in charging infrastructure [84]. The development of the smart grid and the Internet of Vehicles (IoVs) has enabled innovative charging methods such as Vehicle-to-Grid (V2G) and V2V charging.

DIDs, VCs, and DLTs lay the foundation for novel energy trading schemes in V2V environments [76]. In these systems, DIDs are used to submit bids and reserve energy, the seller DID is publicly accessible to verify the legitimacy of the sellers and transactions. The only information stored on the blockchain is the DID Document. Transaction details, such as cost and the amount of energy exchanged, are securely recorded through VCs. DIDs and VCs can be seamlessly integrated into ISO 15118-20 [85], the standard defining communication protocols for EV charging. These technologies offer a robust alternative to the complex, centralized PKI traditionally required by the standard [77].

TABLE VI
TAXONOMY OF SMART HEALTHCARE APPLICATIONS.

Work	Use Case	Main Contributions
[86]	Immunity Passport	An application that verifies COVID-19 antibody test/vaccination certifications.
[87]	Immunity Passport	A blockchain-based privacy-preserving platform for issuing and verifying COVID-19 test/vaccine certificates.
[88]	Immunity Passport	A blockchain-based platform for secure sharing and validation of COVID-19 vaccination certificates stored in IPFS.
[89]	Rare Disease	A rare disease identity system that facilitates communications among different specialists, simplifying the resolution of patient identities.
[90]	Healthcare Data	A privacy-aware access control system for healthcare data based on blockchain and SSI.
[91]	Healthcare Data	An access control system that allows users to directly grant access to their EHRs.
[92]	Federated Learning	A privacy-preserving decentralized learning framework for healthcare systems that leverages VCs to allow clients to participate.
[93]	IoMT Devices Authentication	A DID-based authentication system for smart healthcare systems.
[94]	Personal Data Trading	A blockchain-based personal data trading system that enables users to sell their sensitive information.

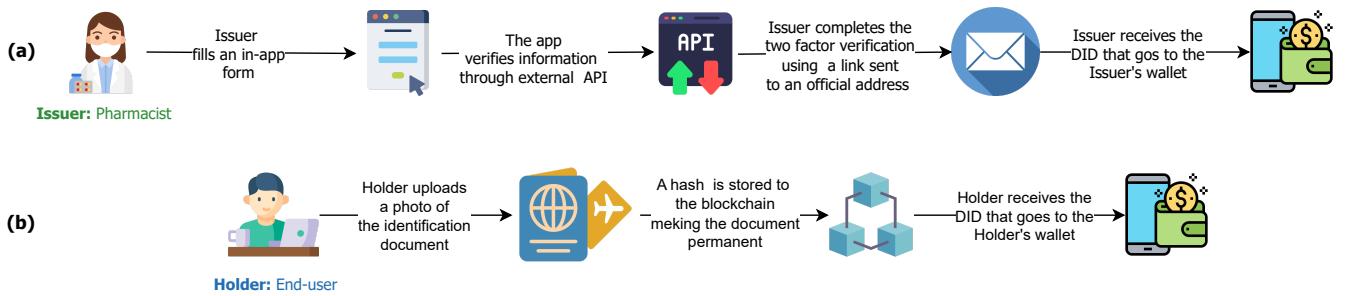


Fig. 11. Onboarding Process: The pharmacist initiates the onboarding by submitting their information, which undergoes verification through external APIs to generate a DID (a). The user authenticates their identity by uploading a document and receiving a DID (b).

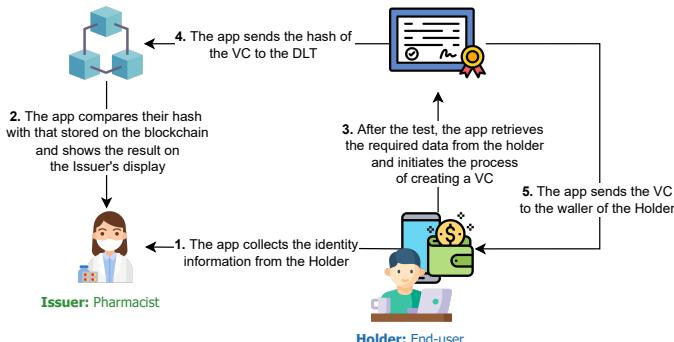


Fig. 12. Certification Process: The user submits their identity information to the pharmacist, who verifies it. After the completion of the medical test, the app retrieves the required data from the holder and initiates the process of creating a VC. Finally, the app sends the VC to the wallet of the Holder.

Another critical concern for EV charging is protecting customer privacy. DIDs and VCs facilitate anonymous yet verifiable charging services, ensuring user privacy while enabling service providers to confirm the legitimacy of users before offering the service. [78]. Users register using a DID and a pseudo-ID, which is employed to generate multiple pseudo-IDs, which are then used for subsequent charging sessions. Both the user and the charging station authenticate each other by verifying the VC of the other party. ZKPs are employed to validate the VC without revealing any additional information about the user.

B. Smart Healthcare

The well-being of individuals has become a central focus in modern society. With the increasing number of healthcare services, the emphasis is on enhancing the health and wellness of patients and elderly individuals, regardless of their location or the time of need [95]. In this context, adopting DIDs and VCs offers significant potential to address critical security and privacy challenges. Below, we summarize key studies from the literature that cover these aspects. Table VI reports the contributions of each reference work.

Healthcare Services. During the COVID-19 pandemic, the concept of *immunity passport* emerged as a potential means to slowly come back to normal lives. Among the various proposed technical solutions, those based on DIDs and VCs have shown the most promise [14]. Mobile apps utilizing these technologies can provide tamper-proof, privacy-preserving certification for test results and vaccinations [86], [87]. In such systems, trusted entities like pharmacies or national health service, providing VCs for essential documents such as test results (e.g., blood tests) or vaccination certificates. These credentials are securely stored in citizen hardware or digital wallets after verification and medical testing are completed. Verifiers are responsible for checking the VCs to determine eligibility for participation in social activities, enforcing necessary health restrictions, and ensuring that only individuals meeting the required criteria are allowed access. Figure 11 illustrates the onboarding process for issuers and users, while Figure 12 shows the main data flows of certification.

Some solutions [88] also incorporate decentralized technologies like the Internet Planetary File System (IPFS) for decentralized off-chain document storing, as storing certificates directly on the blockchain would be extremely expensive in terms of storage and time. Due to the criticality of such information, IPFS stores the encrypted version of VCs, accessible only to authorized entities. The IPFS hash is linked to the citizen DID which serves as the user key pair.

These technologies can also support patients with rare diseases, requiring treatments from multiple care providers and specialists. Effective identity management helps streamline care, avoiding repetitive steps, enabling scalable and collaborative solutions. RDIS [89] is a rare disease identity system that facilitates communications between specialists and resolves patient identities. It involves 4 types of participants, each identified through a unique digital identifier (UDID), a DID implementation tied to a digital profile. Verifiers, such healthcare providers, manually check documents and attest to users credentials. Consumers are all the entities, like specialists, who need to access the Unique DID document of a patient. The other participants are patients and their delegates, which may be needed in case patients are minors or suffer from some pathology that limits them. Verifiers issue and sign attestations attached to patient's UDID document, and consumers verify these attestations through a smart contract, which confirms the user presence in the verifier registry. Every interaction is recorded in an audit log, containing only the DID and a timestamp.

Healthcare Data Management. DIDs and VCs lay the foundation of SSI systems, enabling selective disclosure of user attributes while maintaining user privacy. One notable application is DSMAC [90], a privacy-aware access control system for healthcare data built on blockchain and SSI principles. DIDs authenticate access requests, with access is granted or denied according to the roles defined in the user VC under normal conditions. In emergency situations, the system seamlessly shifts to Attribute-based Access Control (ABAC) model, where permissions adapt dynamically to the contextual attributes included in the VC. In this model, the patient creates the access control policies and embeds them into the DID Document, which is shared on the blockchain. Access to Electronic Health Records (EHRs) can also be managed using VCs, which represent the patient's consent to share specific information under predefined conditions [91]. Thus, individuals can directly issue a VC that determines what resources can be accessed.

The increasing volume of healthcare data can be leveraged by Machine Learning (ML) to support medical professionals through predictive analytics for patient's future health status. However, strict regulations prohibit the processing or sharing of individual health information without explicit consent, hindering data exchange across hospitals and clinics. Federated Learning (FL) [96] offers a promising and effective paradigm, enabling multiple healthcare providers to collaboratively train ML models without sharing raw data. In FL, each participant trains a local ML model and exchanges only model weights, which are further processed (e.g., differential privacy) to

prevent inference attacks. Another critical issue in FL is the lack of trustworthiness among the participants, which can be addressed by allowing a trusted authority, such as a hospital, to facilitate collaboration [92].

The rise of the Internet of Medical Things (IoMT) is also revolutionizing healthcare, with networks of small, power-efficient, and lightweight wireless sensors, enabling healthcare providers to remotely monitor patients [97]. These sensors collect vital health data and assist in making timely medical decisions. For secure data transmission, devices must be registered using a DID and VC, which then generate authentication tokens for interaction with healthcare providers and identification numbers (e.g., hospital web server) [93].

Additionally, DIDs and VCs facilitate the secure trading of personal data [94]. Users can authenticate their identity through their DIDs and claim ownership of data using VCs. If the data owner accepts a buyer's request, they issue a VC that grants the buyer permission to use the purchased data. ABAC models offer highly flexible and fine-grained access control by regulating authorization based on user-defined attributes, which may include sensitive health information.

C. Industry

In recent years, the convergence of information technology (IT) and operational technology (OT) has given rise to a new era known as smart industries [111]. These industries integrate traditional manufacturing processes with cutting-edge technologies like artificial intelligence (AI), data analytics, and IoT, driving and fostering economic growth [112]. As the demand for intelligent, data-driven solutions rises, the software has become a vital part of product development for modern industries.

In this evolving landscape, decentralization has emerged as a key focus due to the need for collaboration and inter-connectivity among stakeholders. DIDs and VCs have attracted significant attention as a tool for enabling secure and interoperable data exchange within industries [113]. Research in this domain has identified four primary areas where DIDs and VCs hold particular promise: smart manufacturing, energy distribution, smart agriculture, and smart supply chain. Table VII summarizes the main contributions of each referenced study in these areas.

Smart Manufacturing. Smart manufacturing leverages advanced technologies to optimize and automate industrial processes [114]. However, centralized approaches often suffer from limitations in flexibility, efficiency, and security, while trust issues with third-party authorities exacerbate these concerns. To address these challenges the integration of DIDs and VCs represents a compelling solution. For instance, DIDs and VCs can be used to combat the counterfeiting of smart devices, such as smartphones [98]. In this scenario, manufacturers generate a unique DID for each smartphone, using the International Mobile Equipment Identity (IMEI) number as an attribute. Specialized DID methods enable verification of the IMEI DID document and ownership management, while VCs serve to prove the device ownership.

The use of VC is also increasing in the context of Digital Twin (DT) technology for realizing smart manufacturing and

TABLE VII
TAXONOMY OF INDUSTRY APPLICATIONS.

Work	Use Case	Main Contributions
[98]	Anti-counterfeiting System	An anti-counterfeiting system for smartphones.
[99]	Firmware/software Updates	A system for securely registering 5G IoT devices and updating their firmware.
[100]	Device Communications	A framework for connecting unknown devices, updating firmware, and providing monitoring features.
[101]	Federated Learning	A framework that enables trustworthy federated learning among unknown clients.
[102]	Federated Learning	A framework that leverages blockchain and decentralized identifiers to simplify the use of FL in industry 4.0 scenarios.
[103]	Smart Grid	A distributed energy system incorporating renewable energy generation and heterogeneous end-users (e.g., residential, commercial, and industrial sectors).
[104]	Smart Grid	A framework for coordinating distributed energy resources.
[105]	Smart Grid	A DID-based attribute-based access control model for the smart grid.
[106]	Agriculture Insurance	A framework that enables trusted agricultural IoT data sharing and provides a decentralized oracle-based access control mechanism for smart contracts in agricultural insurance.
[107]	Food Supply Chain	A system that provides full visibility of processes and food certifications.
[108]	Supply Chain	A model to track assets among different blockchain-based supply chain systems.
[109]	Software Supply Chain	A blockchain-empowered architecture for software bill of materials.
[110]	Product Carbon Footprint Supply Chain	A model that enables trustworthy and confidential sharing of product carbon footprint.

Industry 4.0. DTs, characterized by the seamless integration between the cyber and physical spaces, provide a virtual representation of physical objects, processes, or services by harnessing real-time data from their physical counterparts [115]. The primary objective of DTs is to conduct temporal and predictive analyses, enabling organizations to derive insights that facilitate informed decision-making and enhance operational efficiency [116]. In this context, addressing security concerns is crucial, as data integrity in DTs must be guaranteed. Authentic data, trusted sources, and traceable ownership are essential for effective DT implementation. Robust cryptographic measures are required to protect data during transit, thwarting unauthorized tampering. The SIGNED framework [117] exemplifies how DLT and VCs can enhance data security in digital twin environments. Each functional unit, such as a device or software module, is equipped with a wallet for seamless VC sharing. When issuing a VC, all relevant attributes are encapsulated within a claim, encrypted through a shared secret, and subsequently stored within the VC. This ensures that verifiers can ascertain the integrity of attributes and detect any tampering, while the issuer selectively shares information based on specific requests.

Furthermore, DIDs and VCs can facilitate firmware updates, as demonstrated by the Gnomon framework [99]. IoT devices register their DIDs with an identity hub before delivery, and receive VCs to manage software updates. The software publisher issues a new VC to the identity hub, and the device requests the latest software through its VC, verifying if the software publisher has authorized the update. If the VC references a newer version, the device uses the URL included in the VC to download the update. A DLT can further enhance, firmware updates, and device monitoring [100]. Each device is assigned a DID, certified by the associated DID Document that defines its communication channel. A smart contract-based supervisor manages logging operations and maintains a list of trusted devices. Manufacturers can indicate a secure endpoint in the

DID Document to enable trustworthy firmware downloads.

DIDs and VCs also foster collaboration among unknown participants in FL. For instance, TruFLaaS [101] offers FL as a service, enabling companies to collaborate on shared tasks, such as predicting machine breakdowns to reduce maintenance costs and enhance production capacity. Participation is regulated through VCs issued by the service provider, with the option to revoke credentials when the quality of the submitted models drops a certain threshold. Similarly, FlowChain [102] promotes the adoption of FL in Industry 4.0 by using DIDs to uniquely identify participants and regulate Industrial Internet of Things (IIoT) device participation in FL training.

Energy Distribution. In this subsection, we explore other applications related to energy distribution. DIDs and VCs can be applied in blockchain-based energy management systems to evaluate user credit [103]. Each user has a DID that can be used to verify credit or assess the credit of others, all while preserving privacy, and avoiding the disclosure of sensitive information. VCs are issued by energy system operators to grant users access to the microgrid and P2P trading system. Users can also issue VCs to confirm that a counterpart has either supplied power on demand or bought less than scheduled. These VCs, which form part of the users credit history, are stored on the blockchain, preventing falsification. As illustrated in Figure 13, the collection of VCs issued to a user constitutes their credit.

Flex [104] provides another example of how DIDs and VCs can enhance energy systems. This framework coordinates distributed energy resources by registering stakeholders through DIDs. These identifiers facilitate interactions between stakeholders, such as system operators and retailers, while allowing customers to present pre-defined documentation to authorized parties for attribute validation. For example, a hardware vendor can verify the capacity or model number of the inverter of a rooftop solar system. DIDs and VCs allow users to prove

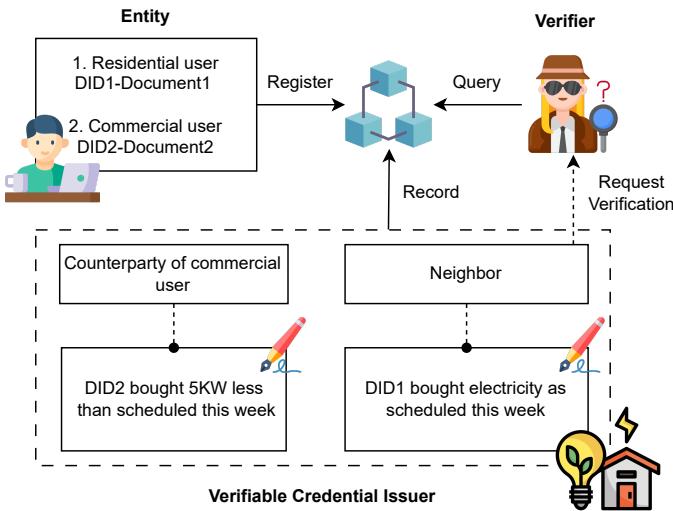


Fig. 13. VCs can be used to determine the user's credit. In the figure, the commercial user with DID₂ has bought less energy than expected, whereas the neighboring user with DID₁ has requested the scheduled energy.

their attributes to any authorized market participant or system without disclosing the underlying information.

In the context of smart grids, ABAC models are widely used for their granularity and flexibility. However, using user attributes for access control can raise significant privacy concerns. To address this challenge and mitigate privacy risks, a promising solution is to implement a DID-based ABAC system [105]. This approach leverages pairwise DIDs to uniquely identify participants, with each identifier tailored to the specific interactions. To further enhance privacy protection, traditional user attributes are replaced with VCs, which attest to the validity of certain user attributes without disclosing sensitive information.

Smart Supply Chain. The integration of DIDs, VCs, and DLTs holds significant promise for enhancing the industrial supply chain within the broader industry ecosystem. These technologies can significantly improve transparency, traceability, interoperability, and logistics operations.

DLTs provide transparency and immutability, which are key to fostering trust and cooperation between supply chain participants, including companies and manufacturers. With DLTs, all participants can access reliable and tamper-proof information, promoting efficient collaboration. On the other hand, DIDs enable the tracking of entities involved in supply chain operations, such as IoT devices and personnel. For instance, each node in the supply chain can require certifications, which are issued as VCs by authorized bodies [107]. These certifications are publicly accessible and verifiable. When a participant seeks a process certification, an off-chain verification procedure ensures they meet the necessary requirements. If successful, the certification body issues a VC stored on the IPFS, with the resulting hash being signed and recorded on the blockchain. Verifiers retrieve the VC by accessing the hash from the blockchain and the corresponding data on IPFS. This mechanism ensures the integrity and authenticity of the certifications, providing a robust trust model within the supply

chain. Figure 14 illustrates how this process leverages IPFS and DLTs to manage DIDs and VCs.

Furthermore, VCs can enhance interoperability across different blockchain-based supply chain systems. An example of this is the Verifiable Supply Chain Credential (VSCC) [108], which extends the traditional VC data model to verify asset alterations tracked across multiple blockchains. This allows seamless data integration from different systems, enhancing the overall efficiency and effectiveness of the supply chain. In shipping, for instance, DIDs and VCs streamline interaction between delivery agents and the mailbox for storing delivered items [118]. The mailbox is identified through an anonymous DID and communicates its availability to the marketplace. For each purchase, the shipping deliverer is provided by the marketplace with a VC that allows access to the mailbox, while the customer receives a VC as proof of withdrawal.

Beyond traditional supply chain functionalities, the combination of blockchain and VCs can revolutionize software development, particularly for sharing the Software Bill of Materials (SBOM) [109]. Blockchain provides a secure and transparent way to store and share data, while VCs ensure the authenticity and integrity of the SBOM information. Oversight authorities may issue VCs certifying that software vendors adhere to secure software development standards and practices. These credentials are then recorded on the blockchain, enabling stakeholders to easily verify the authenticity of the software and its components, thereby promoting trust in software development processes.

VCs can also help achieve trustworthy supply chain exchange for product carbon footprints [110]. This is particularly relevant for manufacturers, as selective disclosure enables them to share only specific information from certifications related to the carbon footprint of their products while safeguarding trade secrets such as supplier details that are typically included alongside the certified carbon footprint value.

D. Other Smart Services

With the rapid advancement of cloud and IoT technologies, urban centers are transforming into smart cities. The smart city concept aims to capitalize on the resources available through ubiquitous devices, offering a wide array of innovative services. A fully smart city ecosystem encompasses components such as IoT devices, interconnected networks, robust data storage systems, and powerful cloud computing infrastructure to support service delivery.

While the potential benefits of smart cities are clear, their implementation remains in its early stages, with no city achieving full digitalization yet. However, by combining DIDs and VCs with other technological breakthroughs, these advancements can significantly enhance smart city services. Table VIII summarizes the key contributions of the reviewed works.

Smart Tourism. The tourism sector continuously seeks innovative solutions that can attract more visitors [129]. On the one hand, the development of smart tourism aims to create a more personalized and ever-adapting experience for tourists while increasing economic, social, and environmental sustainability.

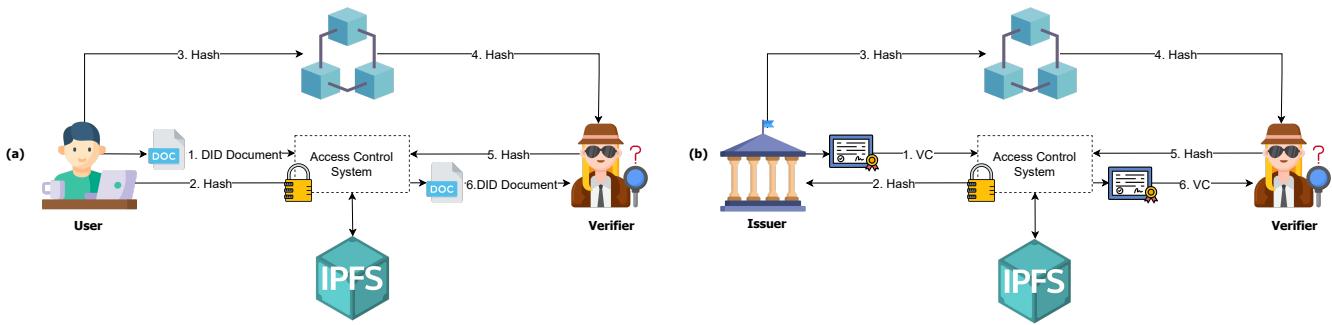


Fig. 14. General workflow for managing DIDs and VCs using DLT and IPFS. In (a), a user uploads their DID on IPFS and publishes the corresponding identifier (i.e., a hash value) on a DLT; such information is then used by verifiers to retrieve the DID document and access to the user's publicly available information. Similarly, in (b), issuers and verifiers perform the same operation referring to VC instead of a DID.

TABLE VIII
TAXONOMY OF OTHER SMART APPLICATIONS.

Work	Use Case	Main Contributions
[119]	Smart Tourism	A smart tourism identity authentication service based on blockchain and DID.
[120]	Smart Tourism	An analysis of how blockchain might offer novel travel experiences within the tourism domain.
[121]	Smart Education	A systematic literature analysis on the use of digital credentials in higher education institutions.
[122]	Smart Education	A mechanism to create secure and machine-verifiable academic credentials.
[123]	Smart Education	A decentralized verification solution for higher education certificates.
[124]	Smart Education	Empirical findings from a cross-border pilot on verifying education credentials between two universities in Italy and Belgium.
[125]	Smart Education	An investigation of how digital credentials can be integrated into the SSI ecosystem to overcome challenges of academic networks.
[126]	Smart Home	An OAuth-based authorization and delegation in smart homes for the elderly.
[127]	Smart Home	A capabilities-based access control system for IoT devices.
[128]	E-commerce	A reliable reputation systems for the e-commerce ecosystem.
[117]	Digital Twin	A framework based on data ownership and verifiability principles, aiming to ensure digital assets in DTs securely protected.

On the other hand, the industry has faced challenges such as fraudulent travel agencies and unqualified part-time guides.

The integration of DID, VC, and blockchain technology offers an effective solution for identity authentication in smart tourism [119]. Tourism companies that want to be authorized can submit identity requests to regulatory authorities in compliance with national standards. Upon successful verification, they receive a DID and VC. To alleviate the burden on the blockchain, IPFS is used to store the DID Documents and VCs, which certify the legitimacy of the smart tourism organization to offer services.

Some countries are reducing their reliance on traditional passports. For example, starting in 2024, Singapore's Airport is implementing automated immigration clearance, allowing travelers to depart without passports using biometric data [130]. Blockchain-based SSI could further enable paperless travel [120]. A tourist can apply for a visa by presenting their DID to the consulate, which releases it as a VC. Such VCs allow the tourist to share identity information when accessing services like hotel reservations and car rentals that require identity verification.

Smart Education. Many higher education institutions still rely on paper-based graduation certificates, leading to inefficiencies such as slow, costly, and easily falsified validation processes [121]. These challenges affect both certificate holders and recruiters. Graduates may face difficulties when accessing services such as applying for further studies or transferring to

other universities, while recruiters may struggle with trust and verifying the authenticity of credential. The adoption of DIDs and VCs is a promising solution to create digital education passports, offering a secure and trustworthy digital alternative to traditional paper-based certificates.

To achieve trustworthiness, certification systems of academic credentials must be transparent. In this direction, blockchain is considered the ideal technology. The process of issuing a VC can be modeled as a series of sub-credentials issued over time, with each certification step being recorded on the blockchain. This creates a dependency graph, allowing verifiers to detect and prevent malicious actions while establishing a publicly verifiable causal relationship between achievements [122]. To further enhance trust, the certification process should be distributed among different officials, reducing the risk of a small group compromising the system. Additionally, blockchain and consortium smart contracts can be used to enforce decentralized verification [123]. Higher education institutions can register issued certificates on the blockchain, allowing recruiters to verify their authenticity and integrity. In this system, consortium smart contract maps the DIDs of registered educational institutions to their respective smart contract addresses. When an academic institution joins the consortium, it must deploy its smart contract and gain approval from other members. The smart contract deployed by each higher education institute manages the registration and retrieval of certificate hashes. Recruiters can utilize an application to

verify certificates, while higher education institutes can use another application to interact with the smart consortium contract to express their intent to join the consortium.

Digital credentials also simplify students' educational services. For example, as shown in Figure 15, university admission offices may need to verify a student's prior degrees from other institutions, potentially located in different countries [124]. Current academic networks like EMREX use PKI to issue and verify digital credentials. However, linking digital identities to students poses a challenge in EMREX as it is not supported by default. To address this, the ELMO2EDS application [125] converts EMREX digital credentials into EBSI diplomas, a suitable SSI data format that enables user authentication.

Smart Home. Smart homes consist of various interconnected devices that collaborate to offer innovative facilities. These devices communicate through a centralized home gateway, acting as a bridge between the smart home and the Internet. This integration enables users to remotely control their homes, offers increased convenience and security to their daily lives [131]. The home gateway also plays a crucial role in managing user access to devices by enforcing predefined access control policies.

In certain situations, external individuals may require access, such as a technician needing to repair a refrigerator. DIDs and VCs offer a promising solution for secure, temporary access. Nevertheless, some smart devices may lack the processing capabilities to handle DIDs and VCs directly. To overcome this limitation, the processing of DIDs and VCs can be delegated to an OAuth server [126]. Considering the example of a broken refrigerator, the technician presents their DID and VC, issued and trusted by their company, to the OAuth server. The OAuth server generates a token granting them access to the refrigerator. In some cases, smart devices may have the resources to independently verify VCs, granting access based on the credential validity. These VCs can include detailed information about the user capabilities over the device, as demonstrated in [127].

Reputation-based Systems. Nowadays, individuals frequently share their opinions through online reviews, expressing preferences for hotels, restaurants, services, and more on platforms like TripAdvisor and Google Reviews. Many people also rely on these reviews when making decisions, such as selecting a restaurant or purchasing a product. However, it is crucial to recognize that these reviews may not always be reliable due to potential biases, whether positive or negative. To address this, VCs can be also leveraged to build more trustworthy reputation systems.

For example, in e-commerce systems, [128] each seller can be identified through a digital identity and, after a purchase, they can issue feedback tokens as VCs to customers. These tokens are used to submit reviews, ensuring the feedback and identity information is authentic and tamper-proof. To encourage participation, clients are rewarded with a discount token from the platform after submitting their review.

Smart Agriculture. Agriculture is one of the most valuable sectors of the global economy. However, recent global warm-

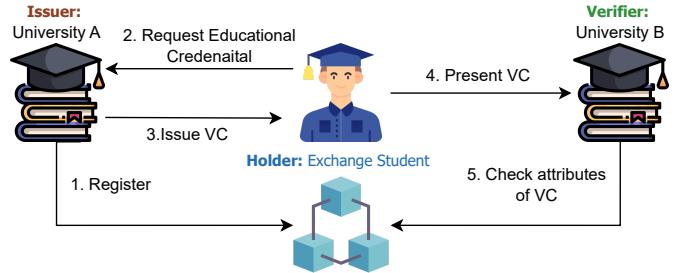


Fig. 15. A student seeks to participate in an exchange program at University B, supported by a VC issued by University A. To ensure the legitimacy of the credits earned at University B, the roles of issuer (University A) and verifier (University B) are exchanged.

ing challenges have significantly impacted food production [132], increasing the number of people experiencing acute hunger. The production risks are primarily caused by extreme weather conditions such as heavy storms and prolonged droughts, which may cause severe losses in crop yield and lead to marginal farmers financial bankruptcy. In response to these challenges, agriculture insurance has emerged as a risk management strategy to support farmers. However, the lack of trustworthiness in agricultural data-sharing platforms and information asymmetries discourage insurers from developing higher-quality insurance schemes. Moreover, smallholder farmers are often reluctant to insure their crops due to limited awareness, high premium costs, delays in payouts, and lack of transparency in the claims process.

The integration of DIDs, VCs, and blockchain can offer the required guarantees to realize agricultural IoT data sharing [106]. In this context, smart contracts also play a crucial role, as they can automate payout to farmers who meet predefined conditions in agricultural risk assessment. However, due to the deterministic nature of blockchain, smart contracts cannot directly access data from external sources such as agricultural IoT. This limitation is overcome through the use of oracles which realizes a bridge between the blockchain ecosystem and the outside world. Each IoT device deployed in farmland is assigned a DID, and the blockchain serves as the source proof for the VCs issued to these devices, based on their attributes.

E. Identity Management

DIDs and VCs were originally proposed as valuable technologies for identity management. This section reviews systems that leverage these technologies for managing user and device identities, and to identify services and resources. Table IX offers an overview of the referenced papers.

Users and Devices. CanDID [133] is a decentralized identity system that enables issuing credentials in a user-friendly manner. The identity subsystem securely ports identities and credentials from existing web services (e.g., social media platforms and online bank accounts), allowing the creation of trustworthy credentials without needing to explicitly generate DID-compatible credentials. CanDID also provides a key recovery service, enabling users to retrieve their keys efficiently.

BIDM [134] is a blockchain-based decentralized identity management system that uses DIDs to identify identities and

TABLE IX
TAXONOMY OF IDENTITY AND ACCESS MANAGEMENT APPLICATIONS.

Work	Use Case	Main Contributions
[133]	Identity System	A decentralized digital identity system.
[134]	Cross-domain Identity	A decentralized cross-domain identity management system based on blockchain.
[135]	Identity System	A distributed identity system for IoT.
[136]	Access Control	An access control model for cross-organization identity management.
[137]	Selective Disclosure	A protocol for the selective disclosure of claims within VCs.
[138]	Identity System	An identity framework that combines SSI and FIDO.
[139]	Naming Protocol	A naming protocol for IPFS content identifiers that enables self-verifiable content items.
[140]	Service Discovery	A P2P discovery system for web services.
[141]	Cross-domain Identity	A cross-chain verification model of DIDs for JointCloud.
[142]	Routing	A protocol enabling routers to self-verify content advertisements.

remove any single-point dependencies. Public keys associated with each identity are retrieved through the blockchain-based identity provider, ensuring secure and trustworthy identity management. BIIdM employs a one-way accumulator to accumulate valid key-value pairs (DIDs and public keys) and support efficient proof of membership. These accumulator states are stored on a blockchain consortium, preventing single point of failure and ensuring cross-domain synchronization. For cross-domain authentication, the identity-relying party retrieves the authenticated entity information and verifies them via the accumulator. To enhance user identity representation, BIIdM divides identities into master and shadow: the master identity corresponds to the DID used within blockchain networks, while the shadow identity is issued by the identity provider and stored offline. SmartDID [135] is another blockchain-based distributed identity system tailored for IoT environments. It features a dual-credential mode and a distributed proof system. The dual-credential mode leveraging commitments and ZKPs to protect the privacy of sensitive attributes, on-chain identity data, and credential linkages.

SSIBAC [136] is an access control model based on the XACML specification, integrating DIDs, VCs, and blockchain technologies to provide privacy and data sovereignty. VCs are encoded in VPs and mapped to access control policies stored in a policy retrieval point. Access requests are regulated through permission validators that bind VPs to attributes, roles, or other data abstractions. Each VC corresponds to an attribute or role defined by an access control policy.

In modern identity and access management systems, privacy preservation is a critical concern. DIDs and VCs offer a novel approach to increase privacy and security by allowing individuals to present credentials without revealing unnecessary data. This is made possible through selective disclosure, a key feature of VCs that enables users to share only a subset of claims while keeping unrelated or sensitive information concealed. For example, when purchasing wine online, a user can disclose only their date of birth to verify their age, while keeping other personal details private. This concept can be extended to other domains, such as healthcare, where a patient might need to prove their insurance coverage without revealing their entire medical history. Numerous selective disclosure mechanisms have been developed over time, leveraging advanced cryptographic techniques like ZKPs and selective disclosure

signatures to ensure security and privacy protection [45]. For example, claims within a VC that represent a diagnostic record can be hidden through HMACs, allowing the patient to selectively disclose data with medical personnel or healthcare service providers [137].

To further enhance security, SSI identity frameworks can integrate additional authentication protocols [138] like FIDO [34]. This combination adds an extra layer of protection, reducing the risk of data breaches and preventing unauthorized access, even in the event of identity theft. Each individual uses a FIDO authenticator, which generates a locally stored key pair serving as their credentials. This key pair is linked to the user DID, facilitating identification and verification of ownership of VCs. For users lacking external authentication devices such as USB tokens, the Trusted Execution Environment (TEE) can act as the FIDO authenticator.

Services and Data. IPFS is a decentralized protocol for storing and sharing data, where each item is identified by a content identifier (CID) derived from a hash function. However, any modification to the data results in a new CID, which can complicate identifier management at scale. Integrating DID and DNS can address this issue [139]. DIDs are used as content names, while DNSlink binds a DID to a CID. The content owner publishes a self-verifiable content item on IPFS, which includes the DID document, proof, signed metadata, and the content itself. The generated DID is associated with the CID through DNSlink, allowing the item to be located by its DID. Whenever the CID is updated due to content changes, the corresponding DNS record is updated as well.

Beyond data storage, DIDs can be extended to service discovery in peer-to-peer networks by using them to identify threads as global resources [140]. DID and VCs enable identity verification among multiple entities from multiple organizations. However, they are usually employed to verify identities within a single blockchain. Facilitating cross-chain DID verification across different blockchains can promote collaboration and trust between entities. For example, in JointCloud - a novel cloud computing paradigm connecting multiple clouds - managing heterogeneous VCs issued by various organizations is achieved through a data structure called a verifiable claim, which can be signed by any entity [141]. To verify claims across blockchains, the verifier executes cross-chain contracts and, if permitted, retrieves and verifies the claims. To further

enhance trust, verifiable claims, signers, and verifiers are assigned a credibility value.

DIDs can also be applied to self-verifiable content advertisement in named data networking (NDN) [142], where content is routed based on identifiers instead of network locations. In this model, content owners use hierarchical DIDs as content names and authorize a publisher to advertise a content name prefix to a specific router. To secure the advertisement process, the content owner generates a DID document containing the JWK representation of a key, which allows the publisher with that key to advertise the content.

F. Lessons Learned

The review of the existing body of research outlines that DIDs and VCs have found applications across seemingly unrelated fields, including smart transportation and smart healthcare. Despite the differences, these technologies are used as integral components in realizing SSI systems across most domains.

A key feature of DIDs and VCs is the capacity to empower individuals with complete control over their data, enabling selective information sharing. Consequently, communication becomes more secure and the risk of potential data breaches is reduced, contributing to building a decentralized and safer digital landscape. Moreover, as underscored by the differences between application domains, these digital identities are utilized across a multitude of platforms and applications, thereby favoring interoperability and improving user experience. Notably, VCs can seamlessly enable access to both educational and healthcare services.

While existing literature primarily focuses on DIDs and VCs as building blocks for SSI, their ability to provide decentralized verification and the use of DLTs extends beyond, paving the way for fulfilling the objectives of various applications. As highlighted in the literature review, DIDs and VCs can be leveraged in many scenarios where decentralized verification and/or immutability are required, with human involvement not being the primary focus. For instance, in vehicular scenarios, these technologies are used to enable secure and verifiable communications between vehicles and roadside units [67]. Similarly, the Gnomon framework [99] employs DIDs and VCs to securely update firmware on devices.

Finally, as discussed in Section IV, there are connections between the chosen implementation and the application domain. For example, referring to the frameworks reported in Table IV, in contexts such as smart agriculture and smart transportation, where entities like smart sensors and vehicles require digital identities, IOTA Identity stands as a natural solution. On the other hand, for individuals who prefer managing their digital credentials through mobile applications, e.g., storing medical certificates or travel information, the Microsoft Entra Wallet offers all the necessary functionalities.

VI. REGULATIONS, PROJECTS & ORGANIZATIONS

Recently, we have been witnessing a growing interest in DIDs and VCs, as demonstrated by the increasing number of regulations, projects, and consortiums emerging worldwide. To

provide a comprehensive overview of the global landscape, this section analyzes the key initiatives that have emerged since 2019. These represent collaborative efforts among various stakeholders, such as government entities, technology firms, research institutions, and standardization bodies.

A. Europe

Europe has always been at the forefront of developing innovative identity management solutions that enable European citizens to use electronic identities (eIDs) for online authentication and communication with online services provided by Member States [143]. This interest in decentralized digital identity predates the rise of DIDs and VCs. In 2014, the European Commission recognized the importance of digital identity with the publication of Regulation 910/2014 on electronic identification and trust services (eIDAS) [144]. This regulation laid the groundwork for European citizens to securely access online services across the European Union (EU) through a standardized set of digital identity credentials.

eIDAS 2.0. The eIDAS regulation is based on the federated identities model, wherein users are registered with an identity provider. This provider enables them to seamlessly share their identities with service providers that place trust in that identity provider. Although this approach provides an SSO experience, it has raised privacy concerns because users do not have direct control over their data, and the identity provider has the potential to aggregate information from multiple services, potentially profiling clients.

To address such challenges, the European Commission proposed an updated version of eIDAS in 2021 known as eIDAS 2.0 [145]. This updated version shifts from a federated to an SSI model aiming to empower users with direct control over their information, sharing only the minimum amount of data required by the service provider to fulfill their request.

In May 2024, the EU Regulation 2024/1183 [22] introduced the European Digital Identity Framework, designed to strengthen secure and user-controlled digital identities. A key element of this framework is the European Digital Identity Wallet (EUDIW) [146], which is expected to catalyze a major shift toward digital identity, with 500 million smartphone users anticipated to regularly use the EUDIW by 2026 [147]. This wallet aims to offer European citizens secure access to both public and private services, online and offline, across Europe through an SSI system. It will simplify daily activities for citizens and businesses by supporting various use cases, such as opening a bank account or obtaining educational credentials. In this ecosystem, each EUDIW is associated with a DID, and the credentials stored in the EUDIW take the form of VCs issued by eIDAS issuers. The verification keys must be publicly accessible by anyone for any use case, ensuring transparency and interoperability.

eSSIF-LaB. The European Self-Sovereign Identity Framework Lab (eSSIF-LaB) [148] is an EU-funded project that focuses on accelerating the adoption of SSI. This initiative represents a next-generation digital identity solution, aiming to revolutionize electronic transactions both online and offline. It achieves this by offering a secure, open, and trustworthy framework.

eSSIF-LaB functions as a collaborative ecosystem that brings together various stakeholders, including governments and enterprises, to simplify the implementation and utilization of SSI technology.

EBSI. The European Blockchain Services Infrastructure (EBSI) [149] is a collaborative effort between the EU and the European Blockchain Partnership (EBP) to establish a unified platform involving all 27 EU MSs, as well as Norway and Liechtenstein. Its primary objective is to create a robust infrastructure that supports seamless cross-border services. For example, one significant application of EBSI lies in leveraging DIDs and VCs to streamline the management of educational credentials. To illustrate the potential of EBSI in this context, notable institutions like the University of Bologna in Italy and the University of Leuven in Belgium have recently participated in a pilot study focused on the verification of educational credentials [124]. This study included verifiable student IDs and transcripts of student records, which can be reliably verified through the EBSI framework.

Regional Initiatives. Besides initiatives directly led by European institutions, there are other projects at the regional level [150]. Among European countries, Finland, Spain, the Netherlands, and Germany are actively working on the development of national SSI frameworks. Moreover, the Spanish Association for Standardization published the first global standard on decentralized identity management based on DLTs in 2021.

GDPR. Additionally, DIDs and VCs offer a flexible and privacy-preserving approach to digital identity management, enabling robust compliance with key GDPR data rights.

- *Right to Be Informed:* Individuals have the right to be informed about the collection and use of their data. With VCs, data sharing is fully under the control of the user, who decides when and with whom to share their credentials. This ensures that individuals are always aware of where their data is being transmitted and for what specific purpose it is being used.
- *Right to Rectification:* In cases where the information within a VC is incorrect or outdated, individuals can request the issuance of the credential with the corrected information, ensuring that their data remains accurate and up-to-date.
- *Right to Be Forgotten:* Users can revoke a VC at any time, rendering it unusable for future verifications and preventing further use of the credential. Additionally, the selective disclosure technique employed by VCs ensures that only the minimum necessary information is shared for any given transaction, significantly reducing the risk of unnecessary data retention by third parties. Finally, VCs may also leverage cryptographic techniques like ZKP, which allows individuals to prove certain properties without revealing underlying personal data, leading to enhanced data minimization.

B. North America

The United States (U.S.) has shown a long-standing interest in trusted digital identities and initiated significant developments starting as early as 2011 when the National Strategy

for Trusted Identity in Cyberspace (NSTIC) was implemented [151]. In 2016, the Department of Homeland Security (DHS) recognized the potential of blockchain-based digital identity technology, awarding grants to enterprises involved in this field [152], including one that funded the establishment of the DID working group within the W3C. Within a year, the DHS began providing financial support, accumulating a total of \$4 million in funding targeted specifically at small and medium-sized enterprises in the DID domain [153].

Over the years, the U.S. government's interest in DIDs and VCs has remained consistent. In June 2023, the DHS further showcased its commitment to advancing this field by publishing a solicitation seeking cutting-edge solutions for a privacy-preserving digital credentialing ecosystem [154]. The DHS aims to incorporate these solutions into various components and offices, including U.S. Citizenship and Immigration Services (USCIS), U.S. Customs and Border Protection (CBP), and the DHS Privacy Office (PRIV). The global success and adoption of DIDs and VCs have fueled this interest. Specifically, the DHS is looking for privacy-preserving components that can seamlessly integrate with existing credentialing systems utilized by the department. Among the valuable technical topic areas identified by the DHS are digital wallets and software-based verifier implementations for mobile devices.

The Government of Canada, through its Digital Identity and Authentication Council of Canada (DIACC), has been actively exploring the use of DIDs and VCs. DIACC is a nonprofit coalition of public and private sector leaders working together to develop a digital identity framework for Canada [155]. One of the key initiatives in this space is the Pan-Canadian Trust Framework (PCTF), which comprises a set of rules, standards, and best practices that define how digital identity and VCs can be used across Canada. The framework aims to establish a trusted and interoperable digital identity ecosystem that facilitates secure and privacy-enhancing transactions. Furthermore, Canada is actively involved in international collaborations and standards development efforts related to DIDs and VCs. For example, the DIACC participates in the W3C Credentials Community Group. In 2018, Canadian public authorities created the Verifiable Organizations Network (VON) to enable governments and organizations to exchange data with VCs used to issue digital licenses, permits, and registration document to legal entities [156].

C. South America

In South America, Argentina is the most active country working on digital identity projects that incorporate DIDs and VCs. The main digital identity project is DIDI [157], which aims to improve levels of trust and break down some of the socioeconomic and financial barriers that impede access to quality goods and services for vulnerable populations. For example, in 2021, to promote financial inclusion, the project began providing farmers in the Gran Cacho region with VCs documenting their sustainable practices. Such credentials contribute to climate risk scores that can be presented to financial institutions looking to promote access to financial credit for rural producers and communities. Recently, the

province of Misiones approved a law allowing the use of blockchain in government management operations. Therefore, the region launched a project to improve the adoption of digital wallets. DIDs and VCs can also facilitate secure and trusted cross-border trade.

South American countries are exploring the use of these technologies to streamline customs processes and enhance trade security. For example, Brazil, Colombia, and Costa Rica are among the main countries involved in Farmer Connect [158], a project that leverages SSI technologies to enable end-to-end traceability across the food and agriculture supply chain while addressing regulatory compliance needs.

D. Asia

Although digital identities are very widespread in Asia, many of the existing solutions do not specifically employ DIDs and VCs. Indeed, most of the approaches are still centralized. However, it is worth noting that they could be easily integrated with these technologies, whose potential has been recently emphasized by the Founder CTO of Aadhaar [159], India's biometric ID system.

South Korea stands out as one of the Asian countries at the forefront of adopting DIDs and VCs with a thriving digital identity ecosystem and numerous ongoing projects [160]. The Korea Financial Telecommunications & Clearings Institute (KFTC) has introduced a blockchain-based digital ID for financial services, while actively participating in the DID Alliance Korea. In 2020, the city of Busan in South Korea launched the Busan Blockchain ID App, enabling citizens to utilize DIDs for accessing various facilities, such as the "multi-child family love" card that provides benefits to households with three or more children. South Korea has also been actively involved in international standardization efforts related to DIDs and VCs, with the Korea Internet & Security Agency (KISA) being a member of the W3C Credentials Community Group.

In late 2023, the Chinese Ministry of Public Security collaborated with the Blockchain-based Service Network (BSN) to introduce RealDID [161], an initiative designed to verify real-name digital identities, encrypt personal data, and provide certification. Furthermore, the Chinese WeBank launched WeIdentity [162], a project aiming to establish a decentralized identity ecosystem using DIDs and VCs. In Hong Kong, using blockchain, DIDs, and VCs have facilitated the development of innovative platforms like ARTRACX Curator [163], which establishes digital identities for fine art and collectibles, ensuring proper intellectual property protection and authentication. These initiatives showcase the diverse applications and forward-thinking approaches to digital identity in the region.

Since 2023, Taiwan's government has been actively working with W3C and IOTA to implement decentralized identity solutions. Taiwan DID [164] is a service that provides Taiwanese citizens with VCs once their residency has been verified. Taiwan DID can be used for digital content subscription services that offer different pricing and content in multiple countries.

E. Africa

DIDs and VCs hold significant potential in addressing identity management challenges in less technologically advanced countries such as those in Africa. Indeed, many of the identity issues experienced in technologically advanced countries, such as Europe and the U.S., have also recently emerged in the second-largest continent. One major concern is the ease of forging digital certificates, as credentials can be easily manipulated using tools like Photoshop. This creates a pressing need to enable easy online verification of credentials for trainees, recruiters, and employers. VCs offer a promising solution in this regard. For instance, Gravity Training, a prominent provider of commercial work-at-height solutions in South Africa, has partnered with Dock Network to embrace the use of VCs [165]. Additionally, local initiatives like Diwala have facilitated the use of VCs in more than 50 institutions across nine African countries [166].

Another critical issue is broadening and facilitating access to financial services. Kiva is a nonprofit organization that aims to enhance financial access for underserved communities. In 2019, Sierra Leone, a West African nation of about 7 million people, launched the National Digital Identity Platform (NDIP) that employs the Kiva Protocol. This platform leverages DIDs and VCs to enable fast, affordable, and secure identity verification for citizens [167]. SSI technology can also be valuable in facilitating birth registration. In Kenya, the use of DIDs and VCs empower relatives to interact with health workers through smartphones, enabling efficient birth registration and linking mothers to their babies [168].

F. Australia and Oceania

Australia has many ongoing and proposed projects focused on storing VCs issued by the government in device-native or state-government wallets and applications. These initiatives aim to facilitate seamless and secure digital identity verification processes. Additionally, Australian jurisdictions are utilizing existing applications and digital wallets for various use cases with particular emphasis on employment and education. For instance, when a recent graduate applies for a job or a higher degree, they may be required to present VCs as proof of their education [169]. However, cross-jurisdictional use cases are also emerging, where citizens may be asked to provide credentials issued by one or more state-level jurisdictions.

In New Zealand, the Digital Identity Services Trust Framework (DISTF) Bill was approved at the beginning of 2023, establishing the legal foundation for an open accreditation scheme. This framework promotes the widespread use of VCs and digital identity in everyday life [170]. For instance, the Credentials Verification Service for the Nursing Council of New Zealand (CVS-NCNZ) enables nurses educated and licensed outside the country to have their credentials verified and authenticated [171]. This service plays a crucial role in allowing qualified nurses to work legally in New Zealand.

G. Lessons Learned

The analysis of emerging regulations, projects, and organizations underscores the global momentum behind DIDs

TABLE X
WORLDWIDE INITIATIVES ON DIDs AND VCS.

Government	Initiative	Description
Europe	eIDAS 2.0	Enables European citizens to access online services across the EU through SSI.
Europe	EUDIW	Secure storage for European citizens to store credentials and identity attributes, and provide them to service providers.
Europe	eSSIF-Lab	An EU project promoting the adoption of SSI through a collaborative ecosystem that simplifies its implementation and utilization for governments and enterprises.
Europe	EBSI	A unified platform, involving all 27 EU members Norway, and Liechtenstein, offering seamless cross-border services.
Canada	PCTF	A set of rules, standards, and best practices that define how VCs can be used across Canada.
Argentina	DIDI	Increases trust and reduces socioeconomic and financial barriers limiting vulnerable populations' access to quality goods.
South Korea	Busan Blockchain ID App	Enables citizens of Busan city to use DIDs for accessing smart city facilities.
China	RealDID	A digital identity service for verifying real-name digital identities, encrypting personal data, and certification.
Taiwan	Taiwan DID	Offers digital services based on the residency of users.
Africa	Diwala	Leverages VCs to easily verify credentials.
Africa	NDIP	Securely identify citizens through DIDs and VCs.
New Zealand	DISTF	A framework to promote the use of VCs in daily lives.

and VCs. These technologies are not only advancing digital identity but also empowering individuals, communities, and organizations across continents. Table X highlights the main initiatives worldwide.

Europe is undergoing a remarkable digital transformation, moving towards the SSI model, as exemplified by eIDAS 2.0. European citizens will be empowered with more control over their data, while the introduction of the EUDIW ensures the secure storage and sharing of DIDs and VCs. Moreover, many countries are actively working on national SSI frameworks, recognizing the importance of tailoring digital identity solutions to local needs and regulations.

In North America, government commitment to promoting the adoption of DIDs and VCs is evident. The U.S. DHS is currently seeking innovative solutions for the privacy-preserving digital credential ecosystem, highlighting the potential of such technologies. The Canadian Digital Identity and Authentication Council is shaping the Pan-Canadian Trust Framework, emphasizing trust and interoperability in the digital identity ecosystem.

Argentina is the most active country in South America. The DIDI project exemplifies how DIDs and VCs can help vulnerable populations to overcome socioeconomic and financial barriers. The use of VCs to promote climate-responsible agriculture and secure rural credit highlights the real-world impact these technologies can have on local communities.

Among Asian countries, South Korea stands out as one of the leaders in adopting DIDs and VCs for digital identity solutions. These initiatives reflect the forward-thinking approach to digital identity and its potential to transform various sectors, including finance and public services. In late 2023, China unveiled plans for introducing a new digital identity service based on DIDs and VCs, supporting the vision that these technologies will experience a significant boost in the near future.

DIDs and VCs are also envisioned as valuable technologies to foster inclusivity and address the unique challenges that affect Africa. For example, they can enhance financial inclusion and secure birth registration. Local initiatives like Diwala and

partnerships with organizations (e.g., Kiva) demonstrate the adaptability and impact of DIDs and VCs in different African contexts.

Finally, Australia and New Zealand are pursuing the widespread adoption of DIDs and VCs. These initiatives focus on enabling citizens to store and use government-issued VCs, providing secure and seamless identity verification. Cross-jurisdictional use cases demonstrate the potential of VCs to enhance digital identity across borders.

VII. CHALLENGES & FUTURE RESEARCH DIRECTIONS

Through the extensive review of DID and VC applications, we have identified several key challenges and outlined future research directions.

A. Standardization

Although DIDs and VCs have been standardized by the W3C, there are several challenges related to content and protocol standardization across different domains. One of the primary concerns is inconsistency in DID method specifications, which vary in format, completeness, information density, and even versioning [172]. These discrepancies pose significant challenges for interoperability, as different DID methods may present varying structures, making seamless integration and verification more difficult.

Similar challenges affect the standardization of VCs. While there are domain-specific efforts, such as the EBSI working on educational credentials for cross-university recognition in Europe [124], many application domains are still in the early stages of adoption. For example, IoT lacks standardized VC data structures for devices, hindering interoperability between IoT networks. Moreover, different industries may adopt domain-specific standards, such as VCs for healthcare, leading to fragmentation if they are not designed to be interoperable.

Standardization concerns extend to the protocols that regulate their use. Many key aspects, particularly those related to security, remain non-normative. There is currently no consensus on cryptographic algorithms, key management practices, or

lifecycle management standards for DIDs and VCs. Additionally, regulatory and legal frameworks are still evolving, which further complicates interoperability and compliance across different jurisdictions. Initiatives like the W3C, ISO standards, and consortiums like Trust over IP (ToIP) [21] are working to address these challenges by promoting unified frameworks and conducting interoperability testing to facilitate seamless integration.

B. Scalability

Decentralized architectures based on DIDs and VCs offer greater scalability than centralized systems. This is a natural consequence because they do not rely on centralized authorities, which often become bottlenecks in traditional systems. DLTs used for storing DID Documents do not remarkably impact scalability regarding verification, as this occurs off-chain. The DLTs are solely used to store and retrieve DID Documents containing issuer and holder public keys. Moreover, a verifier trusting a subset of issuers can locally store their public keys, minimizing ledger interactions.

However, with the increasing adoption of DIDs and VCs, scalability challenges emerge at the system level, especially in ledger storage and maintenance. The exponential increase in digital identities and their associated DID Documents will place higher demands on the ledger. Although registration and updates occur less frequently than verifications, the expanding ledger may increase maintenance and access costs, leading to potential bottlenecks in query efficiency. Additionally, DLT-based systems can face network congestion during peak activity, slowing down data retrieval and raising operational costs.

To address these challenges, mechanisms like indexing, caching, and sharding [52] can improve DID Documents retrieval. Indexing can allow faster lookups, while caching can store frequently accessed data locally to minimize interactions with the ledger. Sharding allows splitting the ledger into smaller, more manageable parts, allowing for parallelized access and reducing latency.

Ongoing research in selective disclosure protocols [45] aims to minimize storage requirements for holders and the amount of data processed during verification. By 2026, identity owners are expected to manage multiple VCs issued by various organizations [147], making it essential to develop mechanisms that enable holders to maintain minimal additional information while selectively disclosing subsets of their claims. These protocols also reduce the data transmitted during verification, alleviating strain on communication channels, minimizing bandwidth usage, and enhancing verification efficiency.

As the volume of issued VCs grows, novel efficient revocation mechanisms become increasingly important to ensure that revocation information can be transmitted and stored without overwhelming the network or consuming excessive storage. Techniques such as cryptographic accumulators and tail files represent promising approaches for optimizing revocation management [59].

C. Usability

The complexity of managing new forms of digital identities may pose a significant barrier to their adoption, particularly

for average users. To address this, by 2026, all EU member states must develop a secure and user-friendly tool that allows European citizens to easily manage their digital identity for accessing public and private services both online and offline (e.g., via Bluetooth or NFC) [173]. This tool will integrate a wide range of digital documents, from academic credentials to driving licenses [174]. To promote their broad adoption, digital wallets must offer intuitive interfaces that abstract the complexity of the underlying technology. Individuals should be able to manage their credentials with simple, clear options for sharing data during verifications while retaining full control over their digital identities. Consent management must be user-friendly, with straightforward prompts clearly explaining the implications of sharing personal information.

To further enhance the user experience, visual workflows and step-by-step guided processes for presenting VCs can make interactions seamless. Additionally, these wallets should support cross-platform interoperability, allowing users to access multiple services without needing different wallets. Interoperability requires adherence to common standards, such as those established by the W3C for DIDs and VCs. This ensures compatibility between different digital identity systems and avoids fragmentation, enabling both users and service providers to integrate digital identities into their existing workflows efficiently.

Moreover, automated features for managing the credential lifecycle should be integrated to reduce the manual burden on users. This includes notifications for credential renewals, automatic updates, and alerts for revocation or expiration, streamlining the process for users unfamiliar with digital identity management. Digital identity systems should be designed to operate seamlessly across multiple devices. By synchronizing credentials between mobile, desktop, and other platforms, users can manage and verify their credentials from anywhere, enhancing both convenience and accessibility. For instance, interoperability between wallets and identity-verification services across platforms and jurisdictions will be critical in creating a cohesive user experience, particularly for travelers or individuals interacting with international services. Wallet interoperability must also account for region-specific legal requirements because differing privacy laws in regions like the EU and the U.S. can influence how VCs are managed and shared, which affects cross-jurisdictional interoperability.

D. Integration

DIDs and VCs represent a paradigm shift in digital identity management, and their integration with the existing digital identity ecosystem presents both opportunities and challenges. One of the major concerns is the lack of a collaborative environment where a community of trusted issuers actively participates. Currently, only a limited number of entities are ready to issue VCs. Although traditional issuers of digital credentials may initially be unwilling to issue signed variants like VCs [133], the potential of these technologies could foster greater collaboration and engagement from them.

DIDs and VCs have the potential to significantly enhance digital identity ecosystems. For example, social media could

leverage these technologies to create verified accounts, addressing concerns about bot activity and creating a safer online environment [175]. In this scenario, VCs play a key role by enabling individuals to prove the authenticity of the information required to create an account. Notably, by employing selective disclosure, only the necessary information would be revealed, preserving user privacy. Similar considerations can be extended to other digital identity environments. DIDs and VCs could eventually replace traditional government-issued IDs. Governments could use VCs to provide secure, tamper-proof identity verification while giving citizens greater control over their data.

However, this transformation also brings technical changes. Identity owners will need a digital wallet to manage their credentials and must undergo a registration procedure that typically involves an initial verification step. Moreover, existing digital identity systems will adapt to support decentralized verification, issuance, and revocation of VCs. For example, service providers would need public keys from a verifiable data registry to directly authenticate the ownership and validity of the presented credentials. While this may face resistance from established identity providers, regulatory frameworks like GDPR could help to overcome such aversion.

To ensure seamless integration, interoperability frameworks like DIDComm [176] can address challenges arising from differences in various factors, including programming languages, vendors, and networks. Additionally, developing robust APIs and SDKs will enable wallet providers to integrate seamlessly with various services, enhancing cross-platform compatibility and reducing fragmentation.

In the short term, broad-scale adoption of these technologies can be achieved by ensuring a smooth transition for legacy systems. Overcoming the inertia associated with legacy infrastructure and enabling seamless interoperability between traditional and decentralized credentialing processes will be key to facilitating the widespread adoption of DIDs and VCs. Thus, novel approaches that build VCs from data, available in existing and unmodified services [177], [178], will be crucial to promote this integration.

E. Security and Privacy

As discussed throughout the paper, although DIDs and VCs offer many security benefits, especially in terms of privacy and fine-grained control over personal data, there are some security concerns that need to be further explored.

DID Management. Granting third parties access to manage DID documents introduces potential vulnerabilities that must be carefully addressed to ensure the integrity and security of decentralized identities. A risk is the possibility of the DID controller impersonating the DID owner by generating a new key pair and modifying the public key in the DID document. This highlights the need for robust authorization and auditing mechanisms to detect and prevent unauthorized modifications to DID Documents.

Currently, the public key associated with a DID is often registered to a blockchain, making it accessible to other nodes of the network. If the corresponding private key is

compromised, key rotation must be initiated. In such cases, the DID owner generates a new key pair and publishes the new public key, signed with the previous one [179]. However, the unpredictable nature of key compromises introduces significant security challenges. Regular key pair updates are one way to reduce the vulnerability window, but this presents a fundamental limitation while it minimizes risk, it does not eliminate it. Key rotation also introduces usability concerns, as frequent updates can be cumbersome for users. Research should focus on flexible key rotation mechanisms that respond dynamically to key compromises, enabling automatic detection and immediate revocation without relying solely on preemptive updates [180]. Integrating MFA, such as one-time passwords (OTP) with key rotation, adds an extra layer of security, making it harder for attackers to steal identities even if a private key is compromised.

VC Revocation. Despite the growing interest in VCs, there remains a significant gap in research focused on developing novel and efficient revocation mechanism. At the time of this paper, only one proposed specification exists, but it has not yet achieved W3C standard status and is on the W3C standards track. As described in Section III, this is the primary method for revoking VCs at present. In addition, there is only one work [59] that introduces a novel mechanism for efficient revocation of VCs, specifically designed for IoT networks.

The field of VC revocation presents a range of unexplored research opportunities. The scalability of current approaches, especially in high-throughput environments or those involving constrained devices, like IoT networks, is underexplored. Additionally, novel approaches that leverage cryptographic accumulators and ZKP could further enhance reliability and security across different contexts. Another promising research direction involves revocation solutions interoperable across various decentralized systems.

Accountability. Ensuring privacy while simultaneously adhering to existing regulations, such as Know-Your-Customer (KYC) [181] and Anti-Money-Laundering (AML) [182], poses a significant challenge for DIDs. DIDs are designed with privacy preservation as a core objective, but reconciling this feature with the need to screen users presents several complexities. Modern systems leveraging DIDs should meet these regulations and be able to screen users of the system. Specifically, they should be able to identify and validate credentials associated with users. This becomes crucial for screening individuals against various lists, such as sanctions lists, to determine if any preventative actions, like blacklisting, are warranted.

Privacy. Research in this domain should explore novel methods that seamlessly integrate privacy-preserving features while ensuring compliance with regulatory measures. This involves developing cryptographic techniques or privacy-enhancing protocols that enables DIDs to provide verifiable information without exposing sensitive details of users.

A key area for further exploration is selective disclosure within VCs, which allows users to reveal only specific claims without sharing unnecessary information. While SD-JWT represents a widely accepted solution, it still presents some

challenges. Notably, the size of the credential grows linearly with the number of claims, which can significantly impact end-user storage requirements. Furthermore, although SD-JWT conceals the content of hidden claims, it discloses the exact number of claims included, which introduces privacy concerns. This detail could be exploited for inference attacks, where adversaries may deduce sensitive information based on the number of undisclosed claims [183], [184].

VIII. CONCLUSIONS

This article presents a comprehensive survey on DIDs and VCs, two building blocks to authenticate and authorize entities in the modern digital landscape, enabling secure and trustworthy communication. We analyze DIDs and VCs in terms of threats and mitigation, implementations, application domains, and regulations. Our analysis of the available implementations offers developers valuable insights into the features of existing libraries, aiding informed decision-making across frameworks. The review of the application DIDs and VCs demonstrates that their utility goes far beyond SSI systems. Furthermore, we examine global initiatives and projects led by governments and political institutions, showcasing the growing adoption of these technologies. Finally, we discuss emerging challenges and outline future research directions, providing a valuable foundation for ongoing studies in this field.

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