Decentralized Identifiers and Self-sovereign Identity in 6G

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Abstract—One of the key challenges for mobile network operators in the future will be to bring together a wide range of new players in the mobile network market under a common umbrella and to orchestrate their innovative technologies to provide economically viable and seamless mobile connectivity to the mobile subscribers. With each new player, be it a cloud, edge or hardware provider, the need for interfaces with secure authentication and authorization mechanisms increases, as does the complexity and operational costs of the public key infrastructures required for the associated identity and key management. While today’s centralized public key infrastructures have proven themselves to be technically feasible in confined and trusted spaces, they do not provide the required security once centralized identity providers must be avoided, e.g., because of limited cross-domain interoperability or national data protection legislation, and state-dependent certification authorities can’t be commonly trusted, e.g., because of geopolitical reasons. Recent decentralized identity management concepts, such as the W3C proposed recommendation of Decentralized Identifiers, provide a secure, tamper-proof, and cross-domain identity management alternative for future multi-tenancy 6G networks without relying on identity provider or certification authorities. This article introduces the concept of Decentralized Identifiers together with the principles of Self-sovereign Identity and discusses opportunities and potential benefits of their application and usage for cross-actor and privacy-preserving identity and key management in the next mobile network generation 6G.

Index Terms—Decentralized Identifiers, Self-sovereign Identity, Decentralized Identity Management, Decentralized Public Key Infrastructures, Verifiable Credentials, 6G

I. INTRODUCTION

Over the past decades, public landline mobile networks (PLMN) have experienced a major structural transformation. They have evolved from closed monolithic hardware and software systems, owned, and managed by dedicated mobile network operators (MNOs), to open, distributed and interconnected systems with a wide variety of actors and stakeholders involved. The liberalization of PLMN ecosystems and the network disaggregation will continue in the future, and new players, such as spectrum brokers, cable, satellite, IoT, or over-the-top (OTT) service providers will take on important roles in the provision of mobile connectivity and related services within converged networks. Consequently, the key role of MNOs needs to be redefined from a sole network operator to a connectivity provider that is responsible to orchestrate the interaction of diverse and sometimes competitive players within the mobile connectivity market. This makes 6G connectivity a multi-domain service that relies on resources distributed across multiple trust domains [1]. So, the more actors are engaged in the operation of a disaggregated and open PLMN, the more cross-domain interfaces are required, and the less do the access and core networks correspond to their original form of closed trusted environments. As a result, in 6G, PLMNs must consequently be considered as zero-trust architectures (ZTAs). But since trustworthiness is one the key design principles of 6G [2], trust must be established between the parties and their network components involved through unified access management.

However, the long specification periods and the incremental opening of PLMN ecosystems have led to a wide variety of authentication or authorization procedures being used in PLMNs today. While mobile subscribers still authenticate in 5G using symmetric cryptography, in roaming, the mutual authentication between MNOs can be carried out with TLS, based on asymmetric cryptography with pre-shared public keys. To apply asymmetric cryptography for authentication purposes throughout the PLMN, public key infrastructures (PKIs) need to be put in place, be operated at each MNO, and be securely interconnected. Besides the additional administrative burden and operational costs there remains a lack of commonly trusted certification authorities (CAs) on a global level. The reasons are manifold, ranging from geopolitical differences to the avoidance of a single point of failure or attack. In 5G, this leads MNOs, as recommended by the GSMA [3], to operate at least one root CA, e.g., for roaming purposes. Nonetheless, the lack of commonly trusted CAs renders the federated identity management approach with interconnected centralized PKIs for 6G complex and insecure.

Meanwhile, subscribers started to pay attention on how their personal data is handled by service providers, resulting in new regional privacy regulations to be applied such as the GDPR in Europe. With more parties involved in the provision of connectivity and related services, compliance with the new privacy and transparency-enforcing regulations becomes increasingly challenging for MNOs because personal...
data is centrally held and processed by MNOs and its partners. Hence, new methodologies to treat identity information in a privacy-preserving manner need to be developed and applied in multitenancy 6G networks to increase transparency for all actors, including the subscribers, and to comply with the latest legal frameworks for the collection and processing of personal information [4].

Accordingly, due to the heterogeneity of today’s identity management (IDM) systems in 4G/5G, the lack of globally trusted CAs and the ever-increasing demand of identity subjects (IS) for personal data protection, a fundamentally different and unified approach to IDM must be adopted in 6G. The digital identities of 6G must meet the following fundamental requirements to be suitable for future-proof IDM in multitenancy 6G networks:

- **Universality**: They do not only represent subscribers, but any IS that is involved in the usage and provision of mobile connectivity and related services, including but not limited to IoT devices, MNOs, virtual mobile network, cloud or IoT operator, manufacturer, or even network functions (NF).
- **Privacy-preserving**: They neither reveal the real identity of an IS nor consist of any personal data related to the real identity of an IS.
- **Interoperability**: They are all unique, machine-readable, of standardized format, and commonly accessible.
- **Verifiability**: They are cryptographically verifiable to enable the referred IS to proof ownership over the digital identity and others to proof the validity of personal data shared by the referred IS.
- **Extensibility**: They are extensible with respect to the supported verification methods due to the diversity of potential application areas.
- **Independence**: They can be created, edited, and used for verification purposes independently of corporates, organizations, and governments, including identity provider and CAs.

However, to achieve independence, IDM in 6G needs to be organized in an entirely decentralized fashion, where the creation and modification of digital identities are being governed equally and in a tamper-proof manner by all actors within a peer-to-peer network.

With the proposed recommendation of Decentralized Identifiers (DID), the W3C has recently introduced a promising method to manage identities in a decentralized manner via a distributed ledger (DL) without identity providers and CAs [5]. The decentralization aspect followed by DIDs bears the inherent potential to unify access management procedures in 6G by using a DL among all involved actors of a PLMN ecosystem as the single source of truth for non-privacy-sensitive access management data. A DID infrastructure makes it also possible to store access authorizations according to the principles of Self-Sovereign Identity (SSI) [6] privacy-preserving as verifiable credentials not centrally, e.g., within the unified data management (UDM), but exclusively at the authorized party, e.g., within the user equipment (UE). Applying DIDs in 6G to decentralize IDM will not only lower the risk of having a single point of failure or attack due to the removal of CAs but they will also enable MNOs to adhere to privacy-by-design principles [7] with SSI. In addition, DID and SSI have the potential to reduce the operational overhead and complexity, and to increase the security and
reliability of cross-actor IDM and - consequently - to foster the harmonization of authentication and authorization mechanisms in future heterogeneous 6G networks.

This article introduces the DID concept and SSI paradigm in the context of 6G, describes how they meet the requirements for IDM in 6G and discusses potential opportunities in form of concrete use cases on the control and user planes.

II. DECENTRALIZED IDENTIFIERS

Today, identifiers for authentication and authorization purposes in PLMNs are organized centrally by MNOs, NGOs, and industry councils such as the ICANN, IOC, or the GSM association. With DIDs, the governance of identities and related keys is equally distributed among all members of a decentralized network through the operation of a common DL. The DL is thereby responsible to persist data in a synchronized and tamper-proof manner among all members of the decentralized network. Already persisted data can't be removed, and new data only be added. Since the data is continuously replicated across all network nodes, all members have access to it. The principal idea of DL-enabled DIDs is to manage and share identifiers and non-privacy-sensitive verification material via the DL while the associated privacy-sensitive personal data are kept locally, off the DL, ideally at the premises of the IS (called DID subject). Like an IS, a DID subject refers to a person or an entity of any kind, e.g., an MNO or NF. The DIDs as persisted in the DL are made of DID identifiers and associated DID documents. Naturally, both are available to all members operating the DL. The DID identifiers are created without a central registration authority, are unique across the DL, consist of alphanumeric strings, and do reference associated DID documents. The latter includes among other information, verification material, e.g., a public key of the DID subject for authentication, authorization, and other purposes. DIDs are extensible, e.g., with respect to the supported verification methods. The DID identifiers and DID documents do not reveal any personal data. There is neither a dedicated identity provider needed to ensure uniqueness of an DID identifier, nor a CA to enable the verifiability of the DIDs. Although DID identifier and the DID document are visible to all members, they can only be updated (data added to make old versions obsolete) either by the DID subject via its private key or by a deputy explicitly appointed by the DID subject, called DID controller. A DID subject can prove ownership of the DID via the private key that is securely stored at the DID subject’s premises and the public key in the DID document. A schematic overview of the DID concept is given in Figure 1 and an exemplary DID document in Figure 2.

The new requirements for IDM in 6G networks regarding universality, privacy-preserving, interoperability, extensibility, and independence are fully met by W3C DIDs. By enabling a DID subject to identify itself to others as the owner of the digital identity, DIDs also support one of the two essential aspects of verifiability. Since the DID concept specifies all functions of a decentralized PKI, it disrupts its centralized counterparts and makes certificates for authentication purposes, e.g., X.509, with CAs entirely obsolete. Instead, it makes use of DL technology (DLT) to enforce trust between all actors governing the DL.

A. Decentralized Identifiers on the Control Plane of 6G

DIDs can be applied to support the key exchange procedures between MNOs and between MNOs and Internetwork Packet Exchange (IPX) providers for roaming purposes. If MNOs and IPX providers are represented by DIDs on a common DL, then the public keys for the mutual authentication can be placed in the associated DID documents. In case public keys need to change over time, DID documents will be updated and synchronized automatically between all nodes of the decentralized network. However, the identifiers need to be exchanged prior to the initial authentication. Afterwards, each party can proof ownership of a DID towards another party by means of the securely owned private keys. The DID specification allows optionally to define service end points in the DID documents. A service end point is meant to be the network address at which a particular service is provided. Changes of gates for roaming signaling can then be securely communicated via changes of the service end points.

A natural appliance of DIDs in 6G is the DID-based subscriber authentication. Xu et al. introduce a new CA-less subscriber authentication scheme [8]. Although not relying on W3C DIDs, Xu et al. could at least show that
subscriber authentication is technically feasible without CAs by decentralizing subscriber IDM. Haddad et al. follows a similar approach and introduces a new authentication and key agreement protocol for 5G that makes use of blockchain-enabled IDM [9]. Raju et al. could even prove that the signaling traffic related to network access can be reduced by up to 40% in cognitive cellular networks if IDM is organized in a decentralized fashion [10].

Since network slicing leads naturally to a core network that is shared by multiple actors like virtual network operators, authentication between NFs becomes mandatory. Today, the mutual authentication is conducted with TLS and CA-issued certificates. In roaming, MNOs are profiting from their collaboration, but virtual network operators are competing on the same territory. To agree on a commonly trusted CA, even if it is the MNO itself, becomes challenging. At least for network slices spanning different trust domains, commonly trusted CAs are required if centralized PKI technology is applied. Following the decentralized principles of DIDs, on the other hand, can enable a CA-less key management across all operators of virtual networks or network slices in a future service-based architecture (SBA). Figure 3 illustrates the concept of having a cross-slice and cross-PLMN decentralized PKI with DIDs.

The Open Radio Access Network (O-RAN) alliance considered O-RAN to be built as a ZTA with TLS and X.509 certificates for the mutual authentication between components of a disaggregated base station, comprising cloud native and physical NFs. O-RANs will be geographically distributed across the whole area of operation which makes them predestined to operate the required key management in a decentralized fashion with DIDs at the edge of the network instead of a centralized PKI within the core network.

The loose decoupling between software components and physical equipment as proclaimed in O-RAN and already introduced as network function virtualization (NFV) in 4G and 5G core networks add additional demarcation lines between hardware, cloud, virtualization, and NF providers. Mutual authentication is therefore not exclusively needed on the NF layer, but up the system chain starting from the physical equipment, over the hypervisor management and the orchestration layers, till the software-defined networking and virtual NF layers. Since NFV developments are still in an early stage, decentralized key management can be considered as a viable solution from the very beginning.

B. Decentralized Identifiers on the User Plane of 6G

The spectrum of opportunities for DID-based authentication is not limited to intra-PLMN or inter-PLMN communication on the control plane, but also encompasses any authentication on the user plane between subscribers and OTT services. While originally, service users had to register with an OTT service exclusively, and thus had to create a digital identity explicitly for this OTT service, nowadays, 3rd parties take on the role of general-purpose identity providers, with Google and Facebook being among the most popular incarnations. These centralized identity providers act as commonly trusted 3rd parties and they do not only provide the identifier, but also manage privacy-sensitive personal data and access to it by other OTT services. With the introduction of the GDPR and the ever-increasing need among service users for more transparency and security regarding digital identity data, the centralized approach via a few international players seems outdated. Not only because service users outsource personal data to external and non-national identity providers - in conflict with the latest privacy-by-design principles -, but also because this makes them dependent on the provider’s security concepts, business practices, privacy regulations, and the legislation of foreign countries.

Fortunately, the concept of DIDs offers a security- and privacy-compliant and independent solution for IDM at the user plane that is safe from enterprise and state intervention. It also enables new non-OTT actors to participate in the value chain around IDM for OTT services. For example, national MNOs can act as DID controllers for their subscribers in the sense of national trust anchors. They can also support resource-constrained terminals in DID-based authentication towards OTT services by providing a network-centric and secure access to the DL. The latter becomes necessary when terminals do not have sufficient technical resources to participate directly in the operation of the DL but must obtain the public keys of the OTT services (anchored in the related DID documents) for authentication purposes. Hereby, MNOs can participate in the operation and governance of the DL and provide exclusive and trusted access to it for their subscribers.

In the IoT domain, IDM became critical for the interoperability of IoT devices from different manufacturers and operators. For autonomous driving or flying with drones, mobile as well as infrastructural IoT devices need to mutually authenticate each other in an ad-hoc fashion to exchange environment information in a secure and trustful manner. Taking a decentralized approach to IDM with DIDs in IoT ecosystems

Fig. 3. Cross-slice and cross-PLMN decentralized PKI with DIDs
would foster the interoperability through the harmonization of ad-hoc authentication mechanisms and enables MNOs to play a pivotal role in IDM for IoT devices through the operation of the required DL and provision of secure access to it in 6G networks. Fedreceski et al. give an outlook of applying DID-based IDM to the domain of IoT devices by comparing it with the current certificate-based approaches [11].

III. Self-sovereign Identity

Self-sovereignty over any information describing an entity is the principal objective behind the latest SSI paradigm. All digital information which are related to an identified or identifiable subject, e.g., the social security number (SSN), should ideally be hold and managed solely by the IS. With SSI, the decision whether at all, to whom and to what extent personal data (credentials) are disclosed lies solely with the IS. To establish a trust relationship between two ISs that have not yet interacted with each other, it is beneficial for ISs to exchange credentials that has been approved by a 3rd party equally trusted by both ISs. So, for the purpose of trust building with SSI, an IS (role: holder) can disclose to another IS (role: verifier) its very own credentials in the form of verifiable credentials (VC) [12] that has been previously approved, digitally signed and handed over to the holder by a 3rd IS (role: issuer). For example, a potential customer (holder) discloses its SSN, as issued by governmental authorities (issuer) as a VC, to an MNO (verifier) for setting up a mobile phone plan. The trust triangle in SSI is only viable if the issuer’s approval of the disclosed claim is cryptographically verifiable by the actor consuming the credentials. SSI thus not only proclaims that credentials should be hold and managed by the IS, but that the credentials could also be approved by a trustful 3rd party and be verified by others. This makes SSI a new fundamental concept to enforce privacy preservation and to enable trust building between actors of different trust domains. SSI can be implemented in a wide variety of ways, e.g., with certificates and CAs. However, the conceptual separation between the commonly accessible DID documents and the privacy-sensitive credentials, as remaining with the ISs, accurately reflects the technical requirements for SSI. Hence, DIDs provide naturally a technical mechanism to implement a decentralized IDM system based on the principles of SSI, without relying on a single identity provider or CA. With DIDs, two ISs can establish a secure connection with mutual authentication (as described in Section “Decentralized Identifiers”), share digitally signed VCs off the DL via the secure point-to-point connection and verify the VCs using the public keys in the available DID documents. DID documents thus do not only contain public keys to authenticate an IS, as described above, but also to verify the authenticity of VCs. VCs thus cover the outstanding aspect of the verifiability requirement for digital identities in 6G, namely the verifiability of personal data by 3rd parties. Figure 4 illustrates the SSI methodology if DIDs are used as the technical foundation.

![Fig. 4. Self-sovereign Identity methodology with DIDs](image)
A. Self-sovereign Identity in the Control Plane of 6G

MNOs, their technical partners, and the subscribers will benefit from the compliance with SSI principles in 6G in many ways. For MNOs and their partners, SSI can bring efficiency improvements, architectural simplifications, and security enhancements while subscribers can experience new and privacy-preserving features in 6G.

With SSI, the change of terminals would be simplified if access permissions are not bound to hardware-based SIM cards, but to the personal identity of the subscriber. Given both MNOs and subscribers are represented by DIDs, an MNO will be able to issue access permissions in the form of VCs directly to the subscriber while the necessary public keys for verification purposes are stored in a tamper-proof manner in the MNOs DID documents. If the subscriber requests connectivity in a roaming situation, the subscriber (holder) hands over the VCs to the visited MNO (verifier) which in turn verifies its validity by means of the home MNO’s public keys in the DID documents. Hence, a change of a terminal device will not lead to a transfer of a SIM card, but to a transfer of the access permission VCs. The latter step is lesser critical because the VCs are anyhow bound to a dedicated DID. Malicious subscribers can’t make use of the VCs unless they act on behalf of the subscriber in the role of a DID controller or got access to the private key of the subscriber’s DID. Since a DL is continuously synchronized across all nodes, a potential revocation of access permissions by the home MNO would almost instantly be taken notice of by any visited MNO through updated entries in the home MNO’s DID documents.

While the subscriber experiences more flexibility with respect to personal mobility, interpreting access permissions as VCs makes it also possible from the visited MNO’s perspective to authorize network access to guests without querying the home MNO [9]. Everything needed for a visited MNO to securely authorize a guest are the VCs as provided by the guest and an access to the DL to query the home MNO’s DID document. Moreover, even in a non-roaming scenario, a home MNO will benefit from access permissions as VCs. The subscriber authentication and authorization could be executed in a decentralized fashion at the edge only, without involving the core network. Since several thousand of IoT devices are expected to register at a single base station in 6G, this would significantly reduce the load on the backhaul links [13]. Salleras et al. make even use of the principles of decentralization to authorize network slice users towards the network slice without letting the users disclose any privacy-sensitive credentials beyond the access permissions [14].

A network authorization, whether a visited MNO is permitted to serve guests from a specific home MNO, can also be encoded as VCs. In this case, a home MNO acts in the role of the issuer and hands over permissions to serve their customers in the form VCs to a partnering MNO (holder). A subscriber (verifier) of the home MNO can then always check whether the VCs provided by a partnering MNO during connection establishment are still valid by querying the necessary DID documents. Network authorizations in form of VCs can even
simplify the process of giving partnering non-3GPP access networks the opportunity to serve guests of a home MNO without requiring a direct link to a 3GPP network, such as the home MNO’s PLMN.

Despite the SSI paradigm being initially introduced to preserve privacy with respect to digital identity-related data for humans, it can also be applied in the control plane of future PLMNs to share authorizations in the form of VCs. In 5G roaming, IPX providers can be actively involved in the signaling between a home and a visited MNO. With the protocol for N32 interconnect security (PRINS), MNOs can grant partnering IPXs rights to alter, on their behalf, the information elements of signaling messages between MNOs and to make the IPX-induced changes verifiable at the message-receiving MNO. PRINS requires complex PKI infrastructures to be present at each MNO and IPX provider and the public keys to be pre-shared among the involved actors. With SSI, authorizations to alter information elements can be issued by the MNO to its partnering IPX providers in the form of VCs while the message-receiving MNO can verify the VCs via the DL. This replaces the complex setup of interacting PKIs of different MNOs and IPX providers with a common decentralized PKI in form of a single cross-domain DL.

Another opportunity to apply SSI principles in 6G in the control plane concerns the NF-to-NF authorization via OAuth 2.0 in the present SBA. Currently, the NRF acts as a trust anchor and provisions authorizations to access resources of a NF to requesting NFs as JSON Web Tokens. A consuming NF attaches the JSON Web Token to the request towards the producing NF, which in turn verifies the validity of the JSON Web Token through a CA. Likewise, at least a single PKI is needed for these purposes within the SBA and multiple interacting PKIs of different MNOs for future cross-SBA network slices. Instead, JSON Web Tokens can be replaced by VCs issued by the NRF, held by the consuming NF, and be verified by the producing NF in case of a service request. The latter example demonstrates that the IS does not necessarily need to be a single human or enterprise to generate benefits in terms of unified authentication/authorization procedures and the elimination of a single point of failure but also a software component in form of an NF or in future multiple-access edge cloud scenarios in the form of 3rd party edge cloud application instances.

B. Self-sovereign Identity in the User Plane of 6G

A subscriber’s benefit of SSI in 6G stems from the possibility to use MNO-collected and -provided context information securely and privacy-preserving with OTT services. MNOs can, for example, issue a subscriber (holder) a VC stating the current geographical location of the subscriber as determined and approved by the MNO. The subscriber is then free to disclose its verifiable location as a VC with any OTT service that requires an MNO-approved location to provide its services. The verification is done by the OTT service via the MNO’s DID documents. The MNO’s role as an issuer for trusted context information opens even new potential revenue streams for MNOs since the context information is already present in PLMNs but only utilized for providing connectivity. Vice versa, MNOs can also benefit from VCs that are issued by OTT services to the subscriber. Taking the example of above, an MNO in the role of a verifier can simplify and thus reduce costs associated with the know-your-customer process during the onboarding of a new customer by verifying the SSN (in form of a VC) as issued by governmental authorities. A costly call to a 3rd party service to verify the credentials of the new customer is no longer necessary. The potential MNO roles within a unified IDM with DIDs and SSI on the user plane are illustrated in Figure 5.

IV. Conclusion and Future Work

The increased complexity of interconnected PKIs, the lack of commonly trusted CAs and the ever-growing demand for privacy protection led to new fundamental requirements for future-proof IDM in 6G networks. The concept of DIDs provides thereby all required conceptual ingredients to design and implement a common, cross-domain, and tamper-proof IDM system for unified and secure intra- and inter-PLMN authentication purposes, without identity providers or CAs. With DID and SSI, 6G networks would even be able to implement privacy-preserving and trust building mechanisms in the control and user planes in which credentials of humans or things are signed by commonly trusted issuers, hold by the ISs according to privacy-by-design principles and still be independently verifiable by 3rd parties. The combination of DID and SSI bears therefore not only the potential to make today’s interconnected and centralized PKIs in 4G/5G obsolete but it - in addition - opens up the opportunity for MNOs to provision trustful and privacy-preserving mobile connectivity and services in future multi-party zero-trust environments.

This article does by no means present a complete list of applications and benefits of DID and SSI for 6G but gives a first glance on the impact decentralized IDM will have on the aspects of trust, security, and privacy at all levels within future 6G networks. Other potential applications in the control plane are, e.g., the DID and SSI-based authentication and authorization of application instances within and across network slices or directly in the mobile edge cloud, and, in the user plane, the mutual DID-based authentication and SSI-based exchange of VCs between subscribers. However, further research is needed and must address open research questions with respect to the technical implementation and architectural integration of DLT in PLMN ecosystems. Further investigations must also cover governance and standardization aspects of operating a DL across competing actors in the PLMN ecosystems and OTT services, and must address the operational overhead induced by DLT, the ability of DLT to scale to billions of subscribers and the expected speed with which DIDs can be created, altered, and synchronized reliably among all nodes of a decentralized IDM system.

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