

Binding of Endpoints to Identifiers by On-Chain Proofs

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Abstract—In many applications, identity management (IdM) is used to associate a subject public key with an *endpoint* at which the subject can be contacted (telephone number, email, etc.). In decentralized applications based on distributed ledger technologies (DLTes), it is desirable for the IdM to be decentralized as well. Currently, endpoints are either verified by who needs it, which is impractical in DLT-based applications, or by a centralized authority, which contrasts with the spirit of DLTes.

In this paper, we show two DLT-based protocols to prove the association between a subject and an endpoint in a decentralized manner, contributing in filling the gap of the current IdM approaches with respect to decentralization. Our protocols are compatible with a wide variety of endpoints. We analyze the security of our protocols and evaluate their performance and cost against the common approaches.

I. INTRODUCTION

The main purpose of identity management (IdM) is to bind an identifier of a subject (usually a public key) with attributes, claims, entitlements, or properties of that subject [1]. In this paper, we focus on the process to bind a subject identifier with an *endpoint* of a *communication technology* (or *channel*). In practice, an endpoint identifies a way to contact the subject. Examples of endpoints are web URLs, IP addresses, email addresses, telephone numbers, postal mail addresses, etc.

Traditionally, IdM has been designed over of centralised architectures and it consequently requires trust in third parties. This might be a problem when an IdM is used in applications designed for Distributed Ledger Technologies (DLTs) that are supposed not to rely on any centralized source of trust. As an example, a subject could store in-chain his/her consent to receive phone calls for marketing purposes. This can be easily implemented storing the consent on-chain in the form of a transaction originating from one of the subject public key(s), but there must be some evidence that the subject's public key is bound to his/her phone number.

While for some applications the possession of an endpoint may be a value per se, in certain countries, certain endpoints are bound by law to a legal person or a natural person. For example, this is the case for telephone numbers in Italy. In these cases, the endpoint verification provides a big added value.

A subject can prove the binding of one of its identifiers with an endpoint by sending or receiving messages on it. This technique is widely used in the context of multi-factor authentication. However, currently, its adoption in a decentralized approach requires endpoint verification to be independently performed by each *verifier* that is interested in this information. This might be a problem, if verifiers are many, since each verification is time and resource consuming (see Section III).

Contribution of the paper. In this paper, we present two DLT-based protocols to perform a *decentralized verification process* capable to write in-chain the *proof* (or *certification*) of the binding between a subject identifier and an endpoint, providing a substantial contribution to a decentralized IdM approach. That proof, can then be used to certify the binding without the burden of the many single verification processes. We analyze the security of our approach against miscertification and denial of service attacks. We also analyze the practical applicability of the proposed protocols with several kinds of endpoints.

Structure of the paper. In Section II, we review the state of the art. In Section III we review basic verification processes and introduce notation. In Section IV, we describe the two protocols to write in-chain the proof of the binding and, in Section V, we analyze their security. In Section VI, we present a first evaluation of our approach and, in Section VII, we discuss applicability aspects with several kinds of endpoints.

II. STATE OF THE ART

IdM is standardized by ISO [1] and there regulations about it (see, for example, *eIDAS* [2] a regulation of the European Union). Protocols and standards related to IdM systems are surveyed in [3]. Identities can be useful across several organizations. For this reason, *single sign-on* approaches, such as Facebook connect, are adopted [4], but usually relays on centralized architectures. The idea of realizing IdM on top of DLTes is a further step toward making IdM independent from a specific organization. In private/permissioned DLTes some kind of trust among participants exists, hence implementing IdM over them does not introduce new conceptual problems. The *Self-Sovereign Identity (SSI)* approach, surveyed here [5],

envisions solutions in which subjects should be able to create and control their own identity, without relying on any centralized authority. In this context, public/permissionless DLTes are fundamental tools. W3C has ongoing efforts to standardize the building blocks of SSI. *Decentralized Identifiers (DIDs)* [6] are controlled by subjects and possibly securely stored in DLTes. DIDs are linked with *DID documents* where attributes are listed. Certain attributes are associated to *Verifiable Claims/Credentials (VC)* [7] which allow the binding between the identifier and the attributes. Our approach can be seen as a tool to implement a verifiable claim to prove the binding between a subject identifier and an endpoint

A realization of this framework is backed by the Decentralised Identity Foundation¹. The relation between DIDs and eIDAS is analyzed in [8].

One of the first attempts to design an IdM system deployed on the blockchain trying to accomplish self-sovereign identities is Namecoin [9]. The uPort system [10] makes use of Ethereum smart contracts and allows subjects to record simple statements about them. Sovrin [11] is an open source identity network built on a permissioned DLT to manage DIDs in which only trusted institutions take part in consensus protocols. ShoCard [12] is a digital identity card for mobile devices. It binds an existing trusted credential (e.g., a passport), with additional identity attributes by means of Bitcoin transactions. The last three systems are also analyzed and compared in [13]. Sora [14] and DNS-IdM [15] are two further recent proposals.

III. BACKGROUND AND NOTATION

Each subject S on a blockchain is associated with at least one pair $\langle p, s \rangle$, where p is a public key and s is the corresponding secret key. We denote by $[m]_s$ or $[m]_S$ the signature of a string m performed by S using s . Each public key of S can be used as a pseudonym for S when S have to be mentioned in any transaction recorded in the blockchain. Subject S can easily prove its association with p by considering a publicly known random string r (a *challenge*), never used before, whose generation is not controlled by S , and providing $[r]_s$. In interactive protocols with two parties, r can be generated by the party that needs the proof. In the blockchain context, r is a cryptographic hash of some *new* piece of data. For example, r can be the cryptographic hash of the last block or a string derived by a new transaction to be submitted (usually a transaction to be valid should be different from all previous ones).

In this paper, we are concerned with a *verifier* V that intends to assess that a subject S possesses an endpoint E . The vast majority of techniques to achieve this result can be traced back to the following two interactive protocols that assumes that V already has an alternative communication mean M with S .

Protocol 1:

- 1) V chooses a challenge code c and sends it to endpoint E .
- 2) S receives c at endpoint E and sends back c to V by M .

Protocol 2:

- 1) V chooses a challenge code c and sends it to S by M .
- 2) S sends back c to V from endpoint E .

These protocols can be adapted to bind the fact that S possesses E with a key pair $\langle p, s \rangle$ of S . In the adapted protocols, S sends back to V a signed version of c ($[c]_s$), actually proving that the subject that knows s also possesses E . In this variation, c is essentially a challenge. In the rest of this paper, we refer to the adapted versions of Protocols 1 and 2 as *basic protocols*.

In a blockchain context, we potentially have a large number of subjects and verifiers. We recognize that the basic protocols have the following drawbacks.

- Each time a different verifier intends to assess if S possesses E , a new verification should be performed. This might be a serious problem if verifiers are many and/or verification has a cost for S .
- Each verification requires to set up an interactive protocol. This means that either S should always be on-line or V should be willing to wait for S to reply to the challenge.

In the spirit of the blockchain, we look for a decentralized solution to this certification problem that does not suffer these two drawbacks.

IV. DLT-BASED PROOFS FOR BINDINGS ENDPOINTS TO SUBJECTS

A *subject* S intends to obtain a *proof* that (s)he owns an end-point E , to be shown to any interested *verifier*. In this section, we show two blockchain-based protocols to achieve this goal in a decentralized manner.

We assume that the communication technology of E can support the exchange of a message at least as large as a (possibly signed) challenge, i.e., a large enough random number. In Protocol 3, the proof-of-possession of E is a proof that S can *send* from E a signed challenge to a number of other subjects. In Protocol 4, vice-versa, the proof-of-possession is a proof that S can *receive* at E a challenge from a number of other subjects.

Formally, S intends to obtain a credible proof of a pair $\langle p, E \rangle$ meaning that S , with public key p , owns E . We can also write $\langle S, E \rangle$ with the same meaning. When S obtains the proof for $\langle S, E \rangle$, we say that S is *certified*. For simplicity, in the following, we assume that all subjects that are already certified are always *on-line*, in the sense that they can

- 1) interact with E by receiving messages at E or sending messages from E ,
- 2) access the blocks of the blockchain including the last one,
- 3) monitor the transactions accepted in the blockchain and react to them.

We relax some of these assumptions in Section IV-C. We now introduce our two protocols.

A. Certifying that a Subject Can Send a Message from an Endpoint

In our first protocol, subject S with public key p obtains the proof-of-possession of endpoint E by sending signed messages

¹ <https://identity.foundation/>

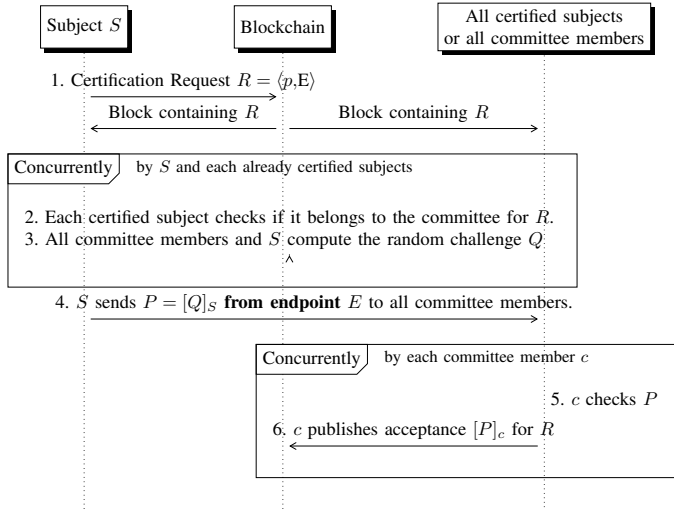


Fig. 1. Sequence diagram for Protocol 3, where S sends signed messages to committee members from endpoint E (see Step 4).

from E to a number of different other subjects. This idea is developed in Protocol 3. The associated diagram is shown in Figure 1. At the end of the protocol, the certificate of possession is published in the blockchain.

Protocol 3:

- 1) **Certification Request.** Subject S creates *certification request* $R = \langle p, E \rangle$ (where p is a public key of S) and publishes $[R]_S$ in the blockchain. Request R reaches all participants as its block is broadcasted.
- 2) **Committee Selection.** A committee of k certified subjects, is randomly selected, on the basis of R , following the procedure detailed below. This is autonomously performed by whoever needs to know the committee composition, comprising S and all DLT participants. Depending on the communication technology, the endpoints of the committee members may be needed, they can be obtained from their certificates published in the blockchain.
- 3) **Random Challenge.** From the block B where R is accepted all committee members and S computes $Q = \text{hash}(R|B)$.
- 4) **Response from E .** S sends from E to all committee members the proof $P = [Q]_S$ that S can send a message from E .
- 5) **Committee checks.** Each committee member c that receives P checks its signature and value of Q .
- 6) **Acceptance.** If checks are successful, c publishes on the blockchain its acceptance $[P]_c$ related to R .

a) *Certificate Verification:* A verifier can check the validity of the acceptance transactions related to R and count them to see if they are k , or above a certain threshold $\bar{k} \leq k$ (see Section IV-C).

b) *Identifiers and summarization:* It is useful to assign to each new certified subject S a sequential *identifier*, denoted $\text{id}(S)$. The assignment can be done by a consensus rule to automatically commit a transaction, in a subsequent block, that

states and summarizes the association $\langle S, E, \text{id}(S) \rangle$ for each $R = \langle S, E \rangle$. This should be done when enough acceptance transactions for R are committed.

c) *Committee selection procedure:* We assume the network comprises N certified subjects. We assume their identifiers to be from 0 to $N - 1$, i.e., there are no holes in the sequence of the identifiers. For a certification request R , we select the committee $C = \{c_1, \dots, c_k\}$, by selecting the identifiers $\text{id}(c_i)$ of its members. Suppose that b is the hash of the block in which the certification request R is committed. We use b as a shared source of randomness.

We need a deterministic method that, for each $i \in \{1, \dots, k\}$, randomly selects an $\text{id}(c_i) \in \{0, \dots, N - 1\}$. This method should depend on R and b and the selection probability should be uniformly distributed among all already certified subjects. It is desirable for this association not to select the same subject twice. However, if $N \gg k$, the probability of accidentally doubly selecting the same subject is negligible.

A very simple approach is to select committee members according to the following rule

$$\text{id}(c_i) = \text{hash}(i|R|b) \bmod N.$$

Note that, given any deterministic association method, as soon as a certification request R is published, each certified subject can autonomously understand if (s)he was selected for the committee to certify R . Further, anyone can easily check if c_i is part of the committee for R as well as enumerate the whole committee.

B. Certifying that a Subject Can Receive a Message at an Endpoint

In our second protocol, a subject S obtains the proof-of-possession of endpoint E by receiving challenges at E from a number of different other subjects. This idea is developed in Protocol 4. The associated diagram is shown in Figure 2. At the end of the protocol, the certificate of possession is published in the blockchain.

Protocol 4:

- 1) **Certification Request.** Subject S creates *certification request* $R = \langle p, E \rangle$ (where p is its public key) and publishes $[R]_S$ in the blockchain. Request R reaches all participants as its block is broadcasted.
- 2) **Committee Selection.** As in Protocol 3, a committee of k members is randomly selected, denoted $C = \{c_1, \dots, c_k\}$.
- 3) **Challenges Generation.** Each member c_i of C generates a random *partial challenge* Q_i .
- 4) **Challenges to E .** Each c_i sends Q_i to endpoint E , where S is supposed to be able to receive it.
- 5) **Proof Publication.** Subject S combines the partial challenges received to obtain the *complete challenge* $Q_1| \dots | Q_k$. S publishes on the blockchain the proof $P = [Q_1| \dots | Q_k|R]_S$ that S has received all partial challenges and hence that S can read messages at E .

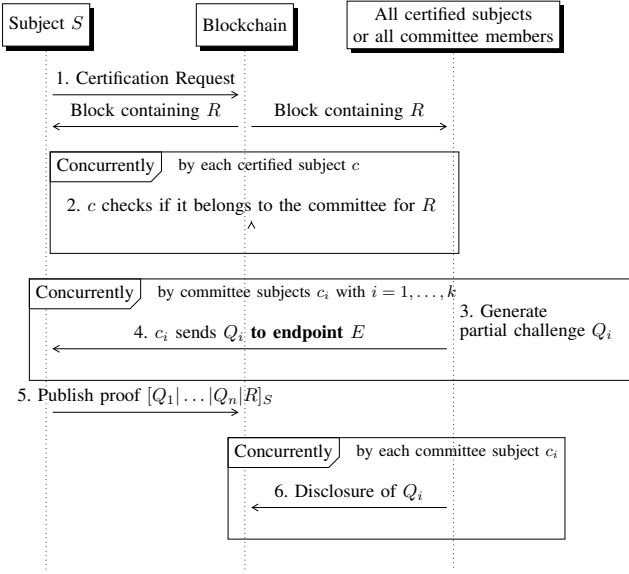


Fig. 2. Sequence diagram for Protocol 4 in which committee members send challenges to endpoint E (see Step 4).

- 6) **Challenges Disclosure.** After P is published, each c_i makes Q_i public by a suitable transaction, also specifying that it is related to R .

a) *Certificate Verification.* A verifier can check the validity of the proof P and then be sure that the association $\langle p, E \rangle$ holds. This verification can be performed by the following procedure, which takes as input $P = [Q_1 | \dots | Q_k | R]_S$.

- 1) Check that $R = \langle p, E \rangle$ is in the blockchain.
- 2) Check that P is correctly signed by public key p .
- 3) For each $i = 1, \dots, k$
 - In the blockchain, look for the transaction containing the challenge disclosure for Q_i related to R performed by c_i .
 - Check that the challenge disclosure for Q_i appears after P in the history.
- 4) If all the previous checks are successful, the proof P is valid and the association $\langle S, E \rangle$ is *certified*.

b) *Identifiers and summarization.* As for Protocol 3, a sequential identifier $\text{id}(S)$ should be assigned to each newly certified subject S . The assignment can be done by a consensus rule in which DLT nodes should execute the above verification process and, if successful, commit a transaction that states the association $\langle S, E, \text{id}(S) \rangle$.

c) *Committee selection procedure.* For the committee selection, the same approach of Protocol 3 can be adopted.

C. Correctness Under Non-Ideal Conditions

Correctness of Protocols 3 and 4 depends on the reliability of the challenge-response process. In particular, the committee members, the endpoint and the communication technology should be reliable. To tolerate a margin of committee subjects that are not on-line (or problems during communication), we can slightly change the protocols.

Protocol 3 can be easily adapted to tolerate a number of missing acceptance transactions by just fixing a suitable threshold $\bar{k} \leq k$ of members that have to accept the proof, for it to be valid.

Protocol 4 can also be adapted. In Step 5, S may not wait for all partial challenges but only for $\bar{k} \leq k$ of them to tolerate a fraction of missing ones.

A further aspect is that there is no reason for committee members to execute the certification protocol. To solve this problem, they should be rewarded for their work. This is not hard to do if the underlying DLT also implements a cryptocurrency, which is often the case.

V. SECURITY

In this section, we introduce our threat model and analyze the security of Protocols 3 and 4 in that model.

A. Threat Model

In analyzing the security of our protocols, we consider the following threats (or malicious objectives).

- Miscertification.** Certification of untrue association of subject S with endpoint E .
- Denial of service (DoS).** Denial of certification for a legitimate $\langle S, E \rangle$ association.

We denote by N the number of certified subjects in the network. In our model, any adversary-controlled (certified or non-certified) subject S may deviate from the protocol in an arbitrary way.

We assume the adversary may ask certification for several pairs $\langle S_i, E_i \rangle$. This is legitimate and easy to achieve, provided that the adversary actually controls the E_i 's and owns keys for subjects S_i 's. These certified subjects may deviate from the protocol and be leveraged to perform malicious actions realizing a *Sybil attack* in our context. However, we assume that only a limited number of subjects m , with $m \leq N$, can be certified by the adversary. This can be enforced in practice in several ways. For example, if the blockchain supports a cryptocurrency, we may regularly charge each certified subject a fee to keep old certificates active. Hence, we can assume that the cost of controlling m subjects is cm where c is the cost for each subject in a certain period of time.

We assume the underlying blockchain technology to be secure. Hence, the adversary

- 1) cannot tamper with the blockchain,
- 2) cannot stop a non-controlled subject from asking to the blockchain to perform a transaction, and
- 3) cannot stop a non-controlled subject from reading from the blockchain the committed transactions.

This also means that the adversary cannot add certifications, delete or tamper with past certificates, or change subject identifiers.

We assume the communication technology of E to be immune from certain specific attacks. For both protocols, we assume no network-level denial of service is possible. For Protocol 3, we assume that the adversary cannot create spoofed

messages that look as if they are sent from E . For Protocol 4, we assume the adversary cannot eavesdrop messages sent to E .

B. Security Analysis

To prove the security of our approach against *miscertification*, we should prove that it is hard for an adversary A to certify an association $\langle S, E \rangle$, when E is not actually controlled by A . We show that the adversary is going to spend $O(N)$ to perform the attack and hence that the security of our approach increases for larger N .

Since the adversary cannot spoof/eavesdrop messages from/to E , if E is not controlled by A , the only way that A has to obtain the certificate is to corrupt a committee controlling at least \bar{k} committee members. The corrupted committee members can assert that they received or sent the messages through E , as stated by our protocols, even if communication occurred using another channel. A committee is formed by k randomly extracted members, out of N total certified subjects, of whose only m are corrupted. The probability $p(m)$ that, in a committee, at least $\bar{k} = \alpha k$ members (with $0 < \alpha < 1$) are controlled by A is given by $p(m) = \frac{\sum_{i=\bar{k}}^k \binom{m}{i} \binom{N-m}{k-i}}{\binom{N}{k}}$. Function $p(m)$ equals $1/2$ at $m = \alpha N$ and it is very close to zero for $m < 3/4\alpha N$. This means that when N increases, the adversary have to corrupt at least about αN subjects to have a reasonable probability to get a corrupted committee. Hence, for k and \bar{k} fixed, the adversary should spend $O(N)$ to perform a miscertification attack with reasonable probability.

To perform a denial of service, A cannot act at the network level or at the blockchain level (by threat model). The only way for A to block a certification process is to force honest members to be less than \bar{k} . To do this, A should corrupt more than $k - \bar{k} = k(1 - \alpha)$ members. Hence, the same argument we showed for miscertification applies where we substitute α with $1 - \alpha$.

VI. PERFORMANCE EVALUATION

In this section we provide a comparison analysis between the basic protocols (see Section III) and the decentralized ones (see Section IV) in terms of latency and of messages transmitted through the endpoint.

We start by analyzing the time taken by decentralized protocols from when the transaction with the certification request R is broadcasted to when the certification is known to all nodes. We call this interval of time the *latency* of the protocol. We assume the delay for creating and signing a challenge to be negligible with respect to other delays involved in the protocol.

We call b the interval of time between two consecutive blocks. For simplicity, we assume b to be constant and the number of transactions a single block can host is greater than the committee size k . We denote by $\bar{b} < b$ the time that a transaction waits before acceptance. The expected value of \bar{b} is $b/2$, if the instant in which a new transaction is received by the blockchain is independent from previous block commit time. We call p , with $p \ll b$, the time to propagate a block

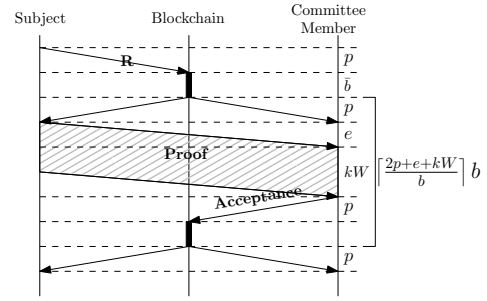


Fig. 3. Timings for Protocol 3.

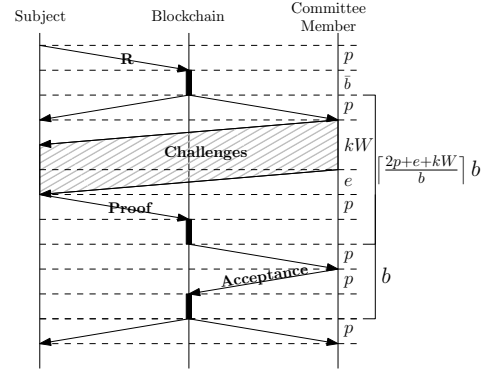


Fig. 4. Timings for Protocol 4.

to all nodes. We assume that the time to propagate a new (still unaccepted) transaction to all nodes is also p . We call W the time that a single message takes to be transmitted to the endpoint and e the time it takes to arrive to destination, hence, k messages are received after $e + kW$ time.

Latency of Protocol 3 is easily derived by observing the diagram in Figure 3 and it turns out to be $\left\lceil \frac{2p+e+kW}{b} \right\rceil b + 2p + \bar{b}$. Analogously by observing the diagram in Figure 4, we derive the latency of Protocol 4, which is given by $\left(\left\lceil \frac{2p+e+kW}{b} \right\rceil + 1 \right) b + 2p + \bar{b}$. We note that, for both protocols, after certification is recorded in the chain, a verifier takes negligible time to check it.

About the latency of basic protocols, let v be the number of verifiers. We assume each verifier verifies $\langle S, E \rangle$ only one time. We assume that the alternative communication mean M between the subject and each verifier has negligible latency and transmission time. The latency of the basic protocols turns out to be $e + vW$.

Concerning the number of messages that have to be transmitted through the endpoint, the basic protocols send v messages overall, while both our protocols send only k messages.

Since our protocols use the endpoint only to transmit a constant number of messages during the certification, they turn out to be advantageous when $v > k$. We note that k can be tuned to obtain a spectrum of tradeoffs between efficiency and security. We also note that our protocols turns out to be advantageous also with respect to latency when W is large and $v \gg k$.

Endpoint	Message	Cost to send one message	Security (Attack difficulty)		Suggested Protocol
			spoofing (P3)	eavesdropping (P4)	
Phone number	SMS	SMS cost	High: telecom op. countermeasures	Medium: it requires physical or logical proximity to the endpoint to miscertify	P3: to charge cost on subject
Phone number	phone call with IVR	phone call cost	Low		P4: for security reason
Postal mail address	letter	stamp	Low		
Email address	email	negligible	Low		
IP address	IP packet	negligible	Low		
Web page	Page change and HTTP response for P3 HTTP GET/POST for P4 (technically complex)	negligible	Medium: proximity required	P3: easier to implement	
DNS name	DNS response (P3 only)	negligible	High: distributed	-	P3
Bank account/IBAN	<i>description</i> field of bank transfer	transfer cost	High	High	P3 or P4

TABLE I

SUMMARY OF ENDPOINT FEATURES. FOR BREVITY, PROTOCOLS 3 AND 4 ARE REFERRED AS P3 AND P4.

VII. APPLICATION CONTEXTS

Nowadays, users already provide proofs-of-possession regarding endpoints in a number of situations. Since, they can be easily turned into use cases for our protocols, we briefly review some of them in this section. Table I summarizes the most common cases. The table reports the endpoint, the kind of message used to prove its possession, the cost, a brief remark about the security regarding its use in our protocols, and the suggested protocol choice. Phone numbers can be certified by both SMS or IVR-based phone calls. Regular postal addresses can be certified by sending letters, even if they may be impractical for large committees. A static web page is easy to use as a broadcast channel in the direction from server to browser(s) for Protocol 3. The opposite direction is also an option, but it requires the web site owner to be able to get details of the GET/POST request. DNS records can also be used as broadcast channel for Protocol 3 while the opposite direction is not available since queries are usually served by third party servers. For bank transfers, a small amount to transfer might also be needed. Concerning security, in most cases eavesdropping is easy if the attacker can reach a position that is close to the endpoint that (s)he intends to miscertify. This is true also for SMS (which are weekly encrypted), but this risk is usually accepted in two-factor authentication procedures. In certain cases, it might be possible to mitigate this risk by using encryption (e.g. as for SSL/TLS for IP), but this may increase complexity and number of messages substantially. For the web, the spoofing attack requires first to eavesdrop the request, hence proximity to endpoint is required. For DNS, responses are generated by third party servers in a distributed manner, hence, the attacker cannot exploit endpoint proximity. Eavesdropping on the committee side is hard, as well. Concerning bank transfers, we assume that confidentiality and integrity are assured by the interbank communication network.

VIII. DISCUSSION AND CONCLUSIONS

We described two blockchain-based decentralized protocols to create verifiable claims regarding ownership of a certain endpoint. We believe that our contribution complements the use of decentralized identifier and is a further step toward a fully decentralized IdM process.

With respect to currently adopted naive approaches, our protocols do not require the subject to be on-line and the endpoint load does not depend on the number of verifications. This makes our approach especially suited in applications where a large number of subjects that are not always on-line are needed to be verified by a large number of verifiers.

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