Highlights

A Blockchain-based Trust System for Decentralised Applications: When trustless needs trust
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- Introduce a novel concept and provision of a universal decentralised trust system that can be integrated into any DApps sharing a same Blockchain platform.
- Present a decentralised trust model with theoretical analysis, algorithms, and simulations.
- Provide the whole agenda of the trust system development including technical solutions, implementation reference, as well as performance evaluation.
A Blockchain-based Trust System for Decentralised Applications: When trustless needs trust

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**Abstract**

Blockchain technology has been envisaged to commence an era of decentralised applications and services (DApps) without the need for a trusted intermediary. Such DApps open a marketplace in which services are delivered to end-users by contributors which are then incentivised by cryptocurrencies in an automated, peer-to-peer, and trustless fashion. However, blockchain, consolidated by smart contracts, only ensures on-chain data security, autonomy and integrity of the business logic execution defined in smart contracts. It cannot guarantee the quality of service of DApps, which entirely depends on the services’ performance. Thus, there is a critical need for a trust system to reduce the risk of dealing with fraudulent counterparts in a blockchain network. These reasons motivate us to develop a fully decentralised trust framework deployed on top of a blockchain platform, operating along with DApps in the marketplace to demoralise deceptive entities while encouraging trustworthy ones. The trust system works as an underlying decentralised service providing a feedback mechanism for end-users and maintaining trust relationships among them in the ecosystem accordingly. We believe this research fortifies the DApps ecosystem by introducing an universal trust middleware for DApps as well as shedding light on the implementation of a decentralised trust system.

1. Introduction

The turn of the last decade brought us to the disruptive Blockchain technology (BC) that provides a trusted infrastructure for enabling a variety of decentralised applications and services (DApps) without the need for an intermediary. To actualise this vision, Smart Contracts (SCs) technology is consolidated into the BC-based infrastructure: SCs are programmed to perform services’ business logic, compiled into byte-code, and deployed onto a BC platform (i.e., replicated into full-nodes in the platform) so that a user can create transactions to execute the business logic implemented in the SCs in a decentralised fashion [9]. This infrastructural BC platform offers some advanced features including immutability, transparency, trace-ability, and autonomy that are promising to effectively implement plentiful DApps from financial services (i.e., cryptocurrencies trading) to numerous services such as digital asset management [1], provenance tracking in logistics and supply-chain [14, 21], and data sharing and processing in the Internet of Things (IoT) [28, 22].

Indeed, various DApps have already been developed and employed into the real-world. For instance, there are over 4000 DApps deployed on top of the Ethereum, Tron, and EOS platforms, serving about 150k active users daily in 2019\(^1\). This is a considerable ecosystem and a huge decentralised peer-to-peer (P2P) marketplace. Although there are numerous challenges due to the limitation of the current BC technology hindering the advancement of DApps, we believe that “everything that can be decentralized, will be decentralized” - David A. Johnston\(^2\). The DApps ecosystem is just in its preliminary state and will be the future of the next-generation Internet.

1.1. Features of DApps

There are different perspectives of DApps definition and system development among the cryptocurrency space. Nonetheless, mutual perceptions were pointed out that a DApp must satisfy some requirements: (i) open source so that participants can audit the system, (ii) application operations and data are recorded and executed in a decentralised BC (e.g., using SCs), and (iii) a crypto token is used to access the service and to contribute to the operations (e.g., token reward) [18, 8]. As of these features, ideally, DApps have the ability to operate without human intervention and to be self-sustaining because the participation of stakeholders is continuously strengthening the systems. According to Vitalik Buterin, DApps generally fall into two overlay categories, namely fully anonymous DApps and reputation-based ones [8]. The first category is DApps which participants are essentially anonymous and the whole service business logic is autonomously executed by a series of instant atomic operations. Pure financial services such as Bitcoin are examples of this. Another example is digital assets trading DApps such as software license, data, and digitised properties in which the ownership can be impecably transferred once a contract (defined and implemented using SCs) has been performed [32].

The second category refers to a type of DApps which business logic requires a reputation-like mechanism to keep
track of participants’ activities for trust-related purposes. For instance, DApps for data storage and computation, similar to Dropbox and Amazon AWS in the centralised space, do require to maintain reputation-like statistic record of peers for service quality and security-related purposes (e.g., anti-DDoS). This requirement of trust is irrelevant to BC technology which supposedly ensures only data security (e.g. for distributed ledgers), autonomy and integrity of the business logic execution programmed in corresponding SCs. The quality of service (QoS) of such a DApp also depends on the service itself (i.e., how well the service handles the business logic defined in the SCs and caters to customers).

1.2. Necessity of a Trust System in DApps Ecosystem

DApps usage always comes with token movement from end-users to service contributors as a result of an incentive scheme, which is crucial to maintaining the service. However, due to the immutable nature, it is practically impossible to revoke any transaction once it is settled onto BC. Thus, a DApp has to make sure that end-users are dealing with trustworthy counter-parties before invoking any SCs’ functions that can lead to a token payment. Intuitively, end-users tend to look for an indication of assurance before using any services. Indeed, a variety of DApps share the same stance on a challenge of lacking a unified decentralised framework to evaluate the trustworthiness of participants (for instance, decentralised storage and computing (similar to cloud storage like Dropbox and Amazon AWS), home-sharing (similar to Airbnb), car-sharing (similar to Uber), or a hotel distribution and reservation service (similar to Booking.com) backed by a BC platform). Consequently, a trust middleware that supports DApps’ end-users to transact with trustworthy counterparts is of paramount importance as it penalises deceptive participants while encouraging authentic ones. As illustrated in Fig. 1, DApps, built upon a BC platform empowered by a decentralised trust system, naturally build up trust with clients and create a virtuous cycles that bolster the whole DApps ecosystem growth.

1.3. Objectives and Contributions

Our objectives are to envision and develop a universal decentralised system that operates along with any DApps to evaluate trust relationships between entities in the ecosystem. This trust system plays as middleware between a BC platform and DApps that provides mechanisms for DApps’ end-users to build up and maintain a trust relationships network among the users. Operations of the system are fully decentralised, transparent, and accessible to all of the participants which are autonomously and flawlessly executed in a trustless fashion. It is also expected to effectively prevent from reputation attacks (e.g., Sybil, White-washing, Self-promoting, and Bad&Good-mouthing) and to dismiss masquerading hostile participants.

The main contributions of this paper are three-fold:

- Introduction to the concept and provision of a universal decentralised trust system that can be integrated into any DApps sharing a same Blockchain platform.
- A decentralised trust model with theoretical analysis, algorithms, and simulations.
- Providing the whole agenda of the real-world development of the system including technical solutions, implementation reference, as well as performance evaluation.

The rest of the paper is organised as follows. Section II briefly brings up background and related work and presents the provision and conceptual model of a decentralised trust system. Section III describes a system design with a trust evaluation model for the proposed system. Section IV provides the algorithms and the theoretical analysis of the trust evaluation model. Section V is to discuss on the technical solutions and the implementation reference for the system development. Section VI is dedicated to the system analysis and discussion. Section VII concludes our work along with the future research directions.

2. Decentralised Trust System Provision for DApps Ecosystem

To craft a BC platform into a mature DApp development environment, fundamental elements must be incorporated such as an Identity Management (IdM), a name registry, a wallet, a P2P messaging for end-users, a browser, and a decentralised trust/reputation system [8]. These elements are core built-in services of a BC-based infrastructure for DApps development.

2.1. Related Work

A large number of trust management mechanisms that have been proposed in various environments including social networks[34], P2P or ad-hoc networks [2], and IoT [37, 31, 30]. Those trust models could be adapted to different scenarios including BC-related environment. However, as the emerging BC technology is in the early stage, there is limited research on trust management for DApps. Most of the
related research is to develop a trust or reputation management platform leveraging the advantages of BC such as decentralisation, immutability, trace-ability, and transparency. In this respect, researchers have proposed BC-based trust mechanisms to fortify specific applications in various environments including vehicular networks and intelligent transportation systems [38, 12], wireless sensor networks [24, 29], or IoT [13, 20]. For instance, W. She et al. [29] have proposed a BC-based trust model to detect malicious nodes in wireless sensor networks by implementing a voting mechanism on-chain, ensuring the trace-ability and immutability of voting information. M. Debe et al. have developed a reputation-based trust model built on top of Ethereum platform for fog nodes in a Fog-based architectural system [6]. The idea is similar in that a reputation mechanism, comprising of several SCs, is implemented on top of Ethereum platform so that clients can give feedback as ratings toward a Fog node when using a service provided by such node. The reputation of a fog node is simply accumulated on-chain from users’ ratings. Being executed on-chain, such ratings and reputation values are immutably recorded in a decentralised fashion, thus ensuring data integrity as well as preventing from Denial of Service (DDoS) attack.

We, instead, look at a different angle of trust in BC-based applications in which a trust system plays a complementary component of the BC platform that cooperates with DApps to empower the ecosystem built on top of the platform. We target to develop a trust system for decentralised services in a BC ecosystem (e.g., Ethereum) in which participants (clients and service providers) interact with each other on-chain in a P2P manner. Our system plays as a unified trust solution working with any DApps. Our previous research in [32] has presented an introductory concept of a unified trust system to strengthen a BC platform. However, it has come without detailed analysis, algorithm, and technical solutions for the development of the decentralised trust system. In this paper, we further explore the concept and the feasibility of a unified trust system as middleware between a BC platform and DApps, as well as provide a proof-of-concept of the decentralised trust system along with the system design, algorithms, technical solutions and implementation reference.

2.2. High-level architecture of BC-based infrastructure and Trust System

For a better understanding of the big picture of the whole BC-based infrastructure including the proposed trust system, we represent the high-level architecture of a full-stack IoT infrastructure by harmonising these components to the IoT and Smart Cities & Communities reference model1. As can be seen in Fig. 2, the BC platform is located in the Service Support and Application Support layer, which is a layer between the Application and Network layers in the IoT architecture. DApps is located in the Application layer. Unlike client-server applications and services whose reputation/trust systems are separately developed, we envisage that DApps in the same ecosystem could leverage a universal trust system, which serves as a fundamental service for the BC-based infrastructure (Fig. 2). This trust middleware exists because DApps’ end-users in an ecosystem are identified by the same IdM and a name registry, and use the same cryptocurrency (e.g., provided by a BC platform) to consume the services.

2.3. High-level Architecture of Trust System

In this sub-section, fundamental elements of a decentralised trust middleware between a BC platform and DApps are described. As can be seen in Fig. 3, the proposed system consists of two basic components named Data Collection & Extraction and Trust Evaluation that collect and aggregate necessary trust-related information and evaluate trust relationships, respectively. These two components are along with North-bound and South-bound APIs for providing trust-related services to DApps and for collecting data from a BC or applications and services, respectively.

2.3.1. Trust Evaluation Mechanism

We adopt the REK trust model proposed in [31, 30] to the DApps ecosystem scenario in which both trustors and trustees are end-users of DApps. In the REK model, a trust relationship is evaluated by assembling three indicators called Reputation (of the trustee), Experience and Knowledge (of the trustor toward the trustee). In DApps scenarios, there is limited availability (or difficult to obtain) of off-chain information (i.e., information that is recorded outside BC) of end-users for evaluating Knowledge indicator as users’ identity is normally pseudo-anonymised and challenging to link to outside world [23]. Instead, transactions between end-users are immutably recorded (and publicly available) on-chain, which can be leveraged for Experience and Reputation evaluations. As a result, in this paper, we employ an adoption of the REK trust evaluation model called DER which only utilises two indicators Experience and Reputation in decentralised environment. Details of the DER trust system is described in the next section.

Generally, after each transaction between entities in a

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1http://itu.int/en/ITU-T/studygroups/2017-2020/20/Pages/default.aspx

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DAp, the trust system enables a participant to give feedback toward its counterpart, thus establishing and updating the *Experience* relationship between the two. By doing this, the trust system maintains an *Experience* network among participants, which is publicly recorded on-chain. This *Experience* network is autonomously updated whenever an entity gives feedback to the other. *Reputations* of all participants are then calculated accordingly, following the idea of Google Page-Rank algorithm. Finally, the trust value between two entity is calculated as composition between *Experience* and *Reputation*.

2.3.2. Data Collection and Extraction

By nature, a BC is a record of a continuous growing list of transactions among end-users which can be analysed to extract a network topology of end-user interactions. Nonetheless, further information about QoS is required to be collected and aggregated in order for the DER trust evaluation mechanism to be performed. Therefore, a decentralised feedback mechanism associated with DApps in a BC platform is required to reflect QoS once end-users (e.g., service clients) successfully carry out transactions with their counterparts (e.g., DApp providers). This mechanism creates a *distributed ledger* that logs users’ feedback (toward a DApps service) along with the information about associated transactions (e.g., end-user ID (*from* address), counterpart ID (*to* address), and *timestamp*). Feedback can be either implicit or explicit which may or may not require human participation [17]. The trust system then extracts feedback and transactions information recorded in BCs as inputs for the DER trust evaluation model (i.e., calculate the Experience and Reputation indicators) in order to evaluate trust relationships between any two peers in the decentralised ecosystem.

3. System Design and DER Trust Model

3.1. Use-cases

For better explanation and clarification, we scrutinise the decentralised data storage services (DDS), in regard to some projects being developed and implemented in the real-world like Storj4, Sia5, and Filecoin6 (built on top of the Inter-Planetary File System7 (IPFS)). Decentralised storage is a promising solution to cooperate or even to take over the conventional centralised cloud storage where data is split into multiple chunks and distributed to storage nodes across a P2P network. These storage nodes, as DDS providers, are expected to reliably store the data as well as provided reasonable network bandwidth with appropriate responsiveness for data owners to retrieve their data. As a reward, such storage nodes are incentivised by crypto tokens. It is worth noting that end-users in DApps ecosystem can be both data owners (DDS clients) and storage nodes (DDS providers). The decentralised storage concept is similar to the legacy P2P file sharing such as BitTorrent8 but fortified with advanced cryptography and encryption mechanisms as well as incentive schemes built upon a BC platform. It is expected to solve the long-standing challenges of single-point-of-control and -failure in centralised data silos, and to bring essential control of data back to the owners whilst discharging full control of cloud server managers.

![Figure 4: Decentralised storage service built on top of a BC platform that incentivizes storage nodes with crypto tokens.](image)

The DDS deploys necessary SCs on top of a BC platform to execute the business agreement between DDS clients (i.e., data owners) and DDS providers (i.e., storage nodes) such as *storage space and period, guaranteed performance* (e.g., *availability, throughput, bandwidth, and latency*), and the *Incentive scheme* (i.e., *Token Reward*) (Fig. 4). Unfortunately, such SCs are *unable to ensure* the QoS of the DDS service provided by a set of storage nodes because (i) it is impractical for the SCs to monitor and enforce the performance of the DDS providers, and (ii) the guaranteed performance can only be measured once the SCs are already invoked. In this regard, a trust system that manages the performance history of the storage nodes and ranks them in order of trustworthiness (to provide high QoS) is of paramount importance.

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4https://storj.io  
5https://sia.tech  
6https://filecoin.io  
7https://ipfs.io  
8https://en.wikipedia.org/wiki/BitTorrent
Table 1

| Notation | Description |
|----------|-------------|
| $Exp_t$  | Experience value at time $t$, $Exp_0$ is the initial value |
| $min_{Exp}$ | minimum $Exp$ value, $min_{Exp} = 0$ if $Exp$ is normalised in $[0,1]$ |
| $max_{Exp}$ | maximum $Exp$ value, $max_{Exp} = 1$ if $Exp$ is normalised in $[0,1]$ |
| $\theta_c$ | Feedback score at time $t$ |
| $\alpha$ | Maximum increase value of $Exp$ in two consecutive transactions, $0 < \alpha < max_{Exp}$ |
| $\beta$ | Decrease rate, $\beta > 1$ |
| $\theta_{co}$ | Cooperative threshold for a feedback score $\theta_c$. A feedback is cooperative if $\theta_i > \theta_{co}$ |
| $\theta_{unco}$ | Uncooperative threshold for a feedback score $\theta_{unco}$. A feedback is uncooperative if $\theta_i \leq \theta_{unco}$ |
| $\delta$ | Minimum Decay value ensuring any Experience relationship degenerates if it is not maintained |
| $\gamma$ | Decay rate controlling the amount of the decay |

3.2. DER Trust Model

In the proposed DER model, trust relationship between two entities is a compound of two elements: Experience (of the trustee toward the trustee) and Reputation (of the trustee). This section describes the mechanisms to calculate such two elements.

3.2.1. Experience mechanism

Experience is an asymmetric relationship from an entity to the another which is built up from previous transactions between the two. Experience is an indicator of trust [31]. For instance, an experience (denoted as $Exp(A, B)$) is constituted from a DDS client (i.e., a data owner, denoted as $A$) to a DDS provider (i.e., a storage node, denoted as $B$) once $A$ invokes an SC to use the storage service offered by $B$. Higher $Exp(A, B)$ value represents higher degree of trust from $A$ to $B$. Essentially, $Exp(A, B)$ increases if $B$ provides high-quality storage service to $A$ (which is reflected by a feedback score $\theta_i$) and vice versa. It is worth noting that feedback can be provided by either clients (e.g., $A$) or an authorised third-party who is monitoring performance of service providers (e.g., $B$). Also, $Exp(A, B)$ gets decay if no transactions taken place after a period of time or a transaction is neutral (i.e., neither cooperative nor uncooperative). The amount of increase, decrease and decay depends on intensity of transactions, feedback scores $\theta_i$ and the current value of $Exp(A, B)$ which can be modelled by linear difference equations and a decay function as follows (notations are denoted in Table 1) [31, 30]:

- **Increase model**

  The current $Exp(A, B)$ (denoted as $Exp_{t-1}$) increases when there occurs a cooperative transaction (at the time $t$, indicated by the feedback score $\theta_i \geq \theta_{co}$) that follows the linear difference equation:

  $$Exp_t = Exp_{t-1} + \theta_t \Delta Exp_t$$  \hspace{1cm} (1)

  where $\Delta Exp_t$ is defined as follows:

  $$\Delta Exp_t = \alpha(1 - \frac{Exp_{t-1}}{max_{Exp}})$$  \hspace{1cm} (2)

- **Decrease model**

  Similarly, $Exp(A, B)$ decreases if the transaction is uncooperative (indicated by the feedback score $\theta_i \leq \theta_{unco}$), following the equation:

  $$Exp_t = Max(min_{Exp}, Exp_{t-1} - \beta(1 - \theta_t)\Delta Exp_t)$$  \hspace{1cm} (3)

  in which $\Delta Exp_t$ is specified in Equation (2). The decrease rate $\beta > 1$ implies that it is easier to lose the $Exp(A, B)$ value due to an uncooperative transaction than to gain it (by a cooperative transaction).

- **Decay model**

  $Exp(A, B)$ decays if there is no transaction after a period of time or a feedback is neutral (i.e., $\theta_{unco} < \theta < \theta_{co}$) and the decay rate is assumed to be inversely proportional to the strength of the experience relationship (i.e., $Exp_t$ value) [27]. Based on these observations, the Decay model is proposed as follows:

  $$Exp_t = Max(min_{Exp}, Exp_{t-1} - \Delta Decay_t)$$  \hspace{1cm} (4)

  $$\Delta Decay_t = \delta(1 + \gamma - \frac{Exp_{t-2}}{max_{Exp}})$$  \hspace{1cm} (5)

3.2.2. Reputation mechanism

The reputation of an entity represents the overall perception of a community regarding the characteristic of the entity such as trustworthiness. In the DApps ecosystem, the reputation of an end-user $U$ (denoted as $Rep(U)$) can be calculated by aggregating $Exp(i, U)$, $\forall i$ are users who have already been transacted with $U$. To calculate the reputation of end-users, we utilise the model proposed in [31, 30] which is based on the standard PageRank [7] and the weighted PageRank [35, 33].

Let $N$ be the number of end-users in the DApps ecosystem, an directed graph $G(V, E)$ is constructed in which $V$ is a set of $N$ users, $E \subseteq \{(x, y) \mid (x, y) \in V^2 \land x \neq y\}$ is set of edges representing experience relationship $E(x, y) = Exp(x, y)$. If there is no prior transaction between $(x, y)$, $E(x, y) = 0$. To enable the reputation model, $G(V, E)$ is divided into two sub-graphs: positive experience $PG(V, PE)$ in which any edge $PE(x, y) = Exp(x, y)$ satisfying $Exp(x, y) > \theta$ and negative experience $NG(V, NE)$ in which any edge $NE(x, y) = Exp(x, y)$ satisfying $Exp(x, y) < \theta$, where $\theta$ is a predefined threshold. $d$ parameter is a damping factor ($0 < d < 1$) introduced in standard PageRank [7]. The reputation for each sub-graph is then calculated as follows:
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- **Positive Reputation**

\[ Rep_{pos}(U) = \frac{1 - d}{N} + d(N_{pos}(i) \times \frac{PE(i, U)}{C_{pos}(i)}) \]  

(6)

in which \( C_{pos}(i) = \sum_{i} PE(i, j) \) representing the sum of all positive experience values that the end-user \( i \) holds (toward other end-users).

- **Negative Reputation**

\[ Rep_{neg}(U) = \frac{1 - d}{N} + d(N_{neg}(i) \times \frac{1 - NE(i, U)}{C_{neg}(i)}) \]  

(7)

in which \( C_{neg}(i) = \sum_{i} (1 - NE(i, j)) \) representing the sum of all complements of negative experience values (i.e., \( 1 - NE(i, j) \)) that the end-user \( i \) holds (toward other end-users).

- **Overall Reputation**

\( Rep(U) \) is the aggregation of \( Rep_{pos}(U) \) and \( Rep_{neg}(U) \):

\[ Rep(U) = \max(0, Rep_{pos}(U) - Rep_{neg}(U)) \]  

(8)

3.2.3. **Trust Aggregation**

Trust relationship between trustor \( A \) and trustee \( B \) is a composite of \( Exp(A, B) \) and \( Rep(B) \):

\[ Trust(A, B) = w_1 Rep(B) + w_2 Exp(A, B) \]  

(9)

in which \( w_1 \) and \( w_2 \) are weighting factors satisfying \( w_1 + w_2 = 1 \). It is worth noting that any end-user once signing up for a DApp is assigned a default value at bootstrap (e.g., \( \frac{1}{N} \)). If \( A \) and \( B \) have no prior transaction then \( Exp(A, B) = 0 \). In this case, \( w_1 = 1 \) and \( w_2 = 0 \); thus, \( Trust(A, B) = Rep(B) \).

4. **Trust Model: Evaluation and Simulation**

This section provides detailed evaluation of the DER trust model including model equations analysis, algorithms, and simulation of the Experience and Reputation models.

4.1. **Experience Model**

4.1.1. **Analysis**

For simplicity, \( Exp \) values and feedback score \( \delta \) are normalised to the range \((0, 1)\) with \( max_{Exp} = 1 \), \( min_{Exp} = 0 \) and the initial value \( 0 < Exp_0 < 1 \).

**Lemma 4.1.** The Increase model defined in Equation 1 is (*) a monotonically increasing function and (**) asymptotic to 1.

**Proof.** From Equation 1 and 2, with \( max_{Exp} = 1 \), we have:

\[ Exp_t = Exp_{t-1} + (1 - Exp_{t-1})\delta_t \alpha \]  

(10)

Subtracting both sides of Equation 10 from 1:

\[ 1 - Exp_t = 1 - (Exp_{t-1} + (1 - Exp_{t-1})\delta_t \alpha) = \]  

\[ (1 - Exp_{t-1})(1 - \delta_t \alpha) = (1 - Exp_{t-2})(1 - \delta_t \alpha)(1 - \delta_{t-1} \alpha) = ... = (1 - Exp_0) \prod_{i=1}^{t} (1 - \delta_i \alpha) \]  

(11)

As \( 0 < Exp_0 < 1 \), \( 0 < \alpha < max_{Exp} = 1 \), and \( 0 < \delta_i < 1 \forall i \); from Equation 11 we have \( 0 < Exp_t < 1 \forall t \).

Therefore, \( Exp \) function defined in Equation 1 is increasing at the increment value between \( Exp_t \) and \( Exp_{t-1} \) is \( \delta_t \times \Delta Exp \), where \( \Delta Exp = \alpha(1 - Exp_{t-1}) > 0 \). Hence, Lemma (*) is proven.

Furthermore, as Increase model is for cooperative transactions, meaning that \( \delta_i \geq \delta_{co}, \forall i \in \{1, \ldots, t\} \); from Equation 11 we have:

\[ 0 < 1 - Exp_t \leq (1 - Exp_0)(1 - \delta_{co} \alpha)^t \]  

(12)

As \( \delta_{co}, \alpha \), and \( Exp_0 \) are the three pre-defined parameters in the range \((0, 1)\); therefore:

\[ \lim_{i \to \infty} (1 - Exp_0)(1 - \delta_{co} \alpha)^t = 0 \]  

(13)

Applying the Squeeze theorem on (12) and (13), we then have:

\[ \lim_{i \to \infty} (1 - Exp_t) = 0 \]  

(14)

In other word, the monotonically increasing \( Exp \) function is asymptotic to 1; hence Lemma (**) is proven.

As the Increase model is monotonically increasing, it is obvious that the Decrease model defined in Equation 3, which is based on \( \Delta Exp \) in Equation 2, is decreasing. The decrements depend on the current \( Exp \), value and the uncooperative \( \delta_t \) feedback score. The decrease rate \( \beta \) depicts the ratio of the decrements compared to the increments, which is normally greater than 1 as the current experience \( Exp \) is “difficult to gain but easy to loose”.

The Decay model defined in Equation 4 ensures that an experience relationship gets weakened if there is no or neutral transactions after a period of time. This is because the decay value \( \Delta Decay \) specified in Equation 5 is always > 0 as \( 0 < Exp_{t-2} < 1 \forall t \geq 2 \); and it is inversely proportional to \( Exp_{t-2} \), implying that a strong relationship persists longer than a weak one.

4.1.2. **Algorithm and Simulation**

Based on the Experience model defined in Section 3.2.1 along with the analysis, the algorithm calculates experience value \( Exp(A, B) \) of entity \( A \) toward entity \( B \) is demonstrated in mathematical-style pseudo-code as in Algorithm 1. It is worth noting that the parameters controlling the Experience model are preset for our demonstration and should be optimised for specific scenarios.

For demonstration purposes, the algorithm is implemented in Matlab with different controlling parameters settings. As
transactions to achieve. For instance, with stronger experience relationships require more cooperative transactions. Let us define the \( A_{pos} \) matrix as follows:

\[
A_{pos} = \frac{1 - \frac{d}{N} \times J + d \times PE \times M^{-1}}{N} \times Rep_{pos}
\]  

(17)

Thus, Equation 16 can be re-written:

\[
Rep_{pos} = A_{pos} \times Rep_{pos}
\]  

(18)
From Equation 18, we can see that \( \text{Rep}_{\text{Pos}} \) is the eigenvector of matrix \( A_{\text{Pos}} \) with the eigenvalue \( = 1 \). Let us define a matrix \( P = A_{\text{Pos}}^T \); thus \( P^T = A_{\text{Pos}} \). Therefore, Equation 18 can be re-written as follows:

\[
\text{Rep}_{\text{Pos}} = P^T \times \text{Rep}_{\text{Pos}} \tag{19}
\]

Equation 19 implies that \( \text{Rep}_{\text{Pos}} \) is the stationary distribution of a Markov chain whose transition probability matrix is \( P \). Let us constitute a discrete-time Markov chain with the transition probability matrix \( P = A_{\text{Pos}}^T \) consisting of \( N \) states and the probability to move from state \( i \) to state \( j \) is \( P(i,j) \). Note that \( \forall i, j \in \{1, \ldots, N\} \), we have:

\[
P(i,j) = A_{\text{Pos}}^T(i,j) = \frac{1 - d}{N} + d \times \frac{PE(i,j)}{m(j)} \tag{20}
\]

The Markov chain can then be constructed as follows:

\[
P(i,j) = \begin{cases} 
\frac{1 - d}{N} + d \times \frac{PE(i,j)}{m(j)} & \text{if } Exp(j,i) \geq \theta \\
1 - \left(\frac{1 - d}{N} + d \times \frac{PE(i,j)}{m(j)}\right) & \text{if } Exp(j,i) < \theta
\end{cases} \tag{21}
\]

where \( \theta \) is the threshold to differentiate positive and negative experiences. This Markov chain is a model of random surfer with random jumps over the experience relationships directed graph \( G(V,E) \) [25, 5, 10]. The graph \( G(V,E) \) is strongly connected with no dangling nodes. This is because any two nodes \((x,y)\) with no prior transaction is set \( Exp(x,y) = 0 \), implying that the edge weight is 0; it does not mean there is no connection. This random surfer Markov chain, apparently, is a weighted PageRank model; as a result, its stationary distribution, \( \text{Rep}_{\text{Pos}} \), exists and is unique [5, 10, 15].

Similarly, \( \text{Rep}_{\text{Neg}} \) vector exists and is unique. Therefore, the overall reputation vector \( \text{Rep} \) exists and is unique.

4.2.2. Algorithm and Simulation

As the existence and the uniqueness are proven, the reputation vector \( \text{Rep} \) of \( N \) end-users in DApps ecosystem can be calculated by solving the matrix equations defined in Equations 6, 7. The traditional algebra method to solve an \( N \times N \) matrix equation (e.g., Equation 6 or Equation 7), whose the complexity is \( O(N^3) \), is impractical when the size of the DApp ecosystem is enormous (e.g., in millions). Instead, the reputations of the \( N \) end-users can be approximately calculated with a predefined accuracy tolerance using an iterative method, which is much more efficient [3, 19]. Thus, the latter approach is utilised to solve Equations 6 and 7, demonstrated by the following pseudo-code (Algorithm 2). As defined in Equation 8, the overall reputation for \( N \) end-users (i.e., \( N \times 1 \) column vector \( \text{Rep} \)) is then simply obtained by adding two vectors \( \text{Rep}_{\text{Pos}} \) and \( \text{Rep}_{\text{Neg}} \), which are the outputs of Algorithm 2.

The simulation of the proposed reputation calculation algorithm are conducted for different DApp ecosystem sizes (i.e., \( N = 1000, 4000, 8000 \) and 16,000) with the error

\[
\text{Alg. 2: Reputation algorithm using iterative method}
\]

\[
\begin{array}{ll}
\text{Input} : (N \times N) \text{ matrix } E \text{ (set of edges in the directed graph } G(V,E) \text{ of } N \text{ end-users)} \\
& \text{Positive reputation } N \times 1 \text{ column vector } \text{Rep}_{\text{Pos}} \\
& \text{Negative reputation } N \times 1 \text{ column vector } \text{Rep}_{\text{Neg}} \\
\text{Parameters Preset} \\
& d \ = \ 0.85; \quad \triangleright \text{ damping factor in standard PageRank} \\
& tol = 1e - 5; \quad \triangleright \text{ Error tolerance} \\
& thres = 0.5; \quad \triangleright \text{ threshold for positive and negative experience} \\
\text{Begin} \\
& \triangleright \text{ Elicit matrices } PE \text{ and } NE \text{ from matrix } E; \\
& PE = \text{zeros}(N, N); \quad \triangleright \text{ initialise zero matrix for } NE \\
& PE = \text{zeros}(N, N); \quad \triangleright \text{ initialise zero matrix for } PE \\
& \text{for } i \leftarrow 1 \text{ to } N \text{ do} \\
& \quad \text{for } j \leftarrow 1 \text{ to } N \text{ do} \\
& \quad \quad \text{if } E(i,j) \geq \text{thres} \text{ then} \\
& \quad \quad \quad \text{PE}(i,j) = E(i,j) \\
& \quad \quad \text{else if } 0 < E(i,j) < \text{thres} \text{ then} \\
& \quad \quad \quad \text{PE}(i,j) = 1 - E(i,j) \\
& \quad \quad \text{Constitute } 1 \times N \text{ row vectors } C_{\text{Pos}} \text{ and } C_{\text{Neg}}; \quad \triangleright \text{ Constitute transition matrices of } PE \text{ and } NE; \\
& \quad \quad C_{\text{Pos}}(i) = \text{zeros}(1, N); \quad \triangleright \text{ initialise zero vector for } C_{\text{Pos}} \\
& \quad \quad C_{\text{Neg}}(i) = \text{zeros}(1, N); \quad \triangleright \text{ initialise zero vector for } C_{\text{Neg}} \\
& \quad \quad \text{for } i \leftarrow 1 \text{ to } N \text{ do} \\
& \quad \quad \quad \text{if } \text{PE}(i,j) > 0 \text{ then} \\
& \quad \quad \quad \quad \text{A}_{\text{Pos}}(i,j) = \frac{PE(i,j)}{C_{\text{Pos}}(i)}; \quad \triangleright \text{ Transition matrix for PE} \\
& \quad \quad \text{if } \text{NE}(i,j) > 0 \text{ then} \\
& \quad \quad \quad \quad \text{A}_{\text{Neg}}(i,j) = \frac{NE(i,j)}{C_{\text{Neg}}(i)}; \quad \triangleright \text{ Transition matrix for NE} \\
& \quad \quad \triangleright \text{ Update } \text{Rep}_{\text{Pos}} \text{ and } \text{Rep}_{\text{Neg}} \text{ based on Equations 6 and 7}; \\
& \quad \quad I = \text{ones}(N, 1); \quad \quad \triangleright \text{ create vector of all ones} \\
& \quad \quad \text{error} = 1; \quad \quad \triangleright \text{ Total error of the current iteration} \\
& \quad \quad \text{while } \text{error} \geq \text{tol} \text{ do} \\
& \quad \quad \quad \text{temp}_{\text{Pos}} = d \times A_{\text{Pos}} \times \text{Rep}_{\text{Pos}} + \frac{(1-d)}{N} \times I; \\
& \quad \quad \quad \text{temp}_{\text{Neg}} = d \times A_{\text{Neg}} \times \text{Rep}_{\text{Neg}} + \frac{(1-d)}{N} \times I; \\
& \quad \quad \quad \triangleright \text{ update error, } \text{error} \text{ of the current iteration} \\
& \quad \quad \quad \text{error} = \sqrt{(\text{error}_{\text{Pos}}^2 - \text{Rep}_{\text{Pos}}^2) + \sqrt{(\text{error}_{\text{Neg}}^2 - \text{Rep}_{\text{Neg}}^2)};} \\
& \quad \quad \text{Rep}_{\text{Pos}} = \text{temp}_{\text{Pos}}; \quad \triangleright \text{ update } \text{Rep}_{\text{Pos}} \text{ vector} \\
& \quad \quad \text{Rep}_{\text{Neg}} = \text{temp}_{\text{Neg}}; \quad \triangleright \text{ update } \text{Rep}_{\text{Neg}} \text{ vector} \\
& \quad \quad \text{Return } [\text{Rep}_{\text{Pos}}, \text{Rep}_{\text{Neg}}] \\
\end{array}
\]
Convergence of the reputation calculation algorithm

![Figure 6: Convergences of the reputation algorithm using interactive method with different sizes of DApp ecosystem](image)

The total error \( \text{err} = 10^{-5} \), which is accurate enough to rank \( N \) end-users in the DApp ecosystem. As depicted in Algorithm 2, the total error \( \text{err} \) is calculated as the Euclidean norm of the vector difference of the \( \text{Rep} \) vector in two consecutive iterations. Fig. 6 illustrates the convergence rate of the algorithm, showing the rapid reduction of the total error as more iterations are carried out. As can be seen from the figure, the algorithm converges in less than 70 iterations (to be exact: 54, 61, 64, and 66 iterations) for four DApp ecosystem sizes \( N = 1000, 4000, 8000 \) and 16,000, respectively. These results suggest that the reputation model well scales for a huge network as the scaling factor is roughly linear in \( \log N \).

5. Technical Solutions and Implementation

This section provides a real-world demonstration for the proposed decentralised trust system and how a decentralised storage service interacts with it. The demonstration is carried out on top of the Ethereum permissionless BC platform in which system components, functionality, technical challenges and solutions are identified as the implementation reference for developers who wish to build a similar system. Source-code of the demonstration can be found here⁹. Smart Contracts source-code is in the `packages/ethereum-core` folder of the repository.

5.1. System Setup

The DDS service and the proposed decentralised trust system are implemented on top of the permissionless Ethereum platform to which fundamental elements for developing a DApp have already been deployed. For instance, in our platform setup, Ethereum account and address are leveraged for IdM, Metamask¹⁰ is for BC browser and a wallet service, and web3j¹¹ are DApps APIs for interacting with Ethereum network (e.g., SCs and end-users). SCs are implemented in Solidity using Truffle suite framework¹² and deployed in an Ethereum test-net (i.e., we use several test-nets including Ropsten, Kovan Rinkeby, and Goerl) for real-world experience. We assume that IPFS storage nodes are also clients of the DApp ecosystem (e.g., Ethereum clients in Ropsten, Kovan or Rinkeby test-net) that get incentivised once providing storage capability (e.g., IPFS storage nodes host and pin the hash of requested files from data owners).

The overall procedure of the setting system is illustrated in Fig. 7. As can be seen in the sequence diagram, a client starts to use the DDS service by making a transaction to a DDS SC (step (1)), which invokes \text{enFeedback} function in \text{FeEx SC} of the trust system to grant the client permission to give feedback to the DDS nodes ((step (3), (4))). Once getting feedback from the end-user (step (5)), experience relationships between the user and the DDS nodes are updated on-chain by executing \text{expCal} function in \text{FeEx SC} (step (6)). On the contrary, as the reputation calculation is resource-intensive, it is impractical to implement the algorithm (i.e., Algorithm 2) on-chain; instead, only the results (i.e., reputation values of entities) are publicly recorded on-chain. This challenge can be circumvented by using Oraclize service, as demonstrated in step (7-1), (7-2), and (7-3) in Fig. 7. With the same reason, \text{Rep SC} is not invoked whenever an experience relationship is updated; instead, it is periodically self-executed - for example, for every 100 blocks.

5.2. Feedback and Experience Smart Contract

This SC, denoted as \text{FeEx}, contains feedback information and experience relationship of any entity \( A \) (i.e., a DDS client) toward entity \( B \) (an IPFS storage node) where a transaction between \( A \) and \( B \) has been carried out (i.e., \( A \) uses the DDS service provided by \( B \) depicted by step (1) and (2) in Fig. 7). \text{FeEx SC} also provides functions for end-users to give feedback and to update experience relationships accordingly. Note that \( A \) and \( B \) are identified by Ethereum address

⁹https://github.com/nguyentb/Decentralised_Trust_Eth_IPFS.git
¹⁰https://metamask.io/
¹¹https://github.com/web3j/web3j
¹²https://truffleframework.com
5.2.1. Ledger Data Model

Necessary information about users’ feedback and experience relationships is permanently recorded on-chain using state variables defined in FeEx SCs. These state variables are as a public distributed ledger comprised of the full history of state transitions of all experience relationships between any two entities. It is convenient to obtain the latest information of any experience relationship as Ethereum supports key-value data format and the latest state of the ledger (recording the most recent experience relationships information) can be found in the most recent block.

FeEx SC stores a state variable, called FeExInfo, in its contract storage in form of nested key-value pairs using Ethereum built-in mapping type as follows:

```solidity
struct FeExStrut {
    uint expValue;
    uint fbScore;
    bool perFlag;
}
mapping (address => mapping (address => FeExStrut))
public FeExInfo;
```

FeExInfo consists of information about the relationship from A toward B, specified in FeExStrut data structure: (ii) Exp(A, B) value, (iii) feedback score, and (iv) a flag indicating whether A has permission to give B feedback. Any parties or SCs can easily access FeExInfo recorded on-chain to obtain desired information for their purposes.

5.2.2. Functionality

The FeEx SC contains two main functions: (i) enFeedback enables revokes permission of a data owner A to give feedback to storage node B by updating the permission flag in FeExInfo with associated transaction ID; and (ii) expCal calculates Exp(A, B) value and updates FeExInfo whenever A gives feedback to B. The enFeedback function is called by an SC of the DDS service once a transaction has been carried out (illustrated by step (3) in Fig. 7).

The expCal implements the experience calculation function following Algorithm 1 proposed in Section 4.1. It is worth noting that as there is no global time server synchronised among nodes in the Ethereum BC platform so that the implementation of the decay model is not straightforward. To circumvent this challenge, expCal determines time in Algorithm 1 using block height (block.number property) so that Exp(A, B) decays every a number of blocks if no transaction occurred between A and B during the period.

5.3. Reputation Smart Contract

5.3.1. Ledger Data Model

Reputation SC, denoted as Rep, records positive reputation and negative reputation of all users (e.g., IPFS storage nodes) using two state variables RepPosInfo and RepNegInfo, respectively. The data model for the two state variables is a mapping between a user’ address and a value:

```solidity
mapping (address => uint)
public RepPosInfo;
mapping (address => uint)
public RepNegInfo;
```

These two state variables play the role of a public distributed ledger permanently recording a full history of state transitions of the positive and negative reputation of all users.

5.3.2. Functionality

The reputation calculation algorithm (Algorithm 2) performs matrix multiplication with numerous iterations that requires a large number of operations and local variable manipulations. Consequently, the resource-consumption and the gas cost for executing this algorithm on-chain are extremely high, which is infeasible to be implemented in Rep SC. To bypass this challenge, off-chain storage and calculations appear as a promising solution. The catalyst of this solution is that high-volume data and resource-intensive tasks should be stored and processed off-chain; only results of the off-chain tasks are piggybacked for on-chain ledgers and/or calculations. However, as an SC must be deterministically executed, there might be a room for ambiguity if SC executions rely on information from off-chain sources. In addition, this practice could turn a decentralised system into a centralised one due to the dependency on an external source of information. This dilemma is known under the term: “Oracle problem” [36]. The following section will describe in detail how Rep SC can accomplish the off-chain reputation calculation while mitigating the Oracle problem.

5.4. Off-chain Computation for Reputation

Oracle problem could be mitigated by leveraging a decentralised trusted provider to feed required data into SCs. For instance, Oraclize13 deploys an SC on Ethereum platform as an API for other SCs to interact with the outside world14. The Oraclize SC works as a bearer that gets required data from an external source and delivers the data to the requested SCs in a decentralised fashion. Furthermore, to alleviate the ambiguity, it (ii) provides authenticity proof as an assurance for data integrity. In the implementation, we follow this Oraclize solution to calculate users’ reputations off-chain.

Assume that there is already an off-chain server, called RepCalService, that implements Algorithm 2 to calculate positive and negative reputations and provides an API (e.g., REST API) to retrieve the calculation results. The implementation of this off-chain service is straightforward: it queries the Ethereum BC to obtain experience relationships stored in FeExInfo and the current reputations values from RepPosInfo and RepNegInfo state variables as inputs for Algorithm 2. Rep SC then periodically calls this service to update the reputation values in a decentralised fashion using Oraclize solution. The below implementation reference shows how to execute these tasks. Specifically, Rep interacts with the

---

13 https://docs.provable.xyz/
14 https://github.com/provable-things/ethereum-api/blob/master/oraclizeAPI_0.4.sol
Oraclize service by importing the Oraclize SC (i.e., `prov
ableAPI.sol`) to make a query to `RepCalService` using ora
clizeQuery() function. A callback function also needs to be
implemented in order to get the results from the query and
to update `RepPosInfo` and `RepNegInfo` accordingly.

```solidity
import './provableAPI.sol';
contract Rep is usingProvable {
    function oraclizeQuery() {
        // make an Oraclize query to the service using URL
        oraclize_query("URL", RepCalService_API_URL);
    }

    function __callback(bytes32 _requestID, string _result) {
        // only Oraclize is permitted to invoke the function
        require (msg.sender == oraclize_cbAddress());

        // update RepPosInfo & RepNegInfo
        RepPosInfo[addr] = getRepPos(_result, addr);
        RepNegInfo[addr] = getRepNeg(_result, addr);
    }
}
```

5.5. Integration of DDS service and Trust System

Supposedly, the DDS service implements some SCs for
data storage business logic between data owners and storage
nodes, which is out of the scope of this paper. The main
focus of the paper is that once a transaction has been accom-
plished between a client and an IPFS storage node, the en-
Feed back function in the `FeEx` is invoked that enables the
owner to give feedback to its counterpart, which will estab-
lish experience and trust relationships (step (2) in Fig. 7).
For this reason, a DDS SC (i.e., the caller SC) defines an in-
terface of `FeEx` SC (i.e., the callee SC) and calls it with the
callee’s contract address as demonstrated as follows:

```solidity
contract DDS {
    function ePayment(address _storageNode, unit _amount, string _datahash) {
        ...;
        if (success) {
            //call FeEx using deployed address scAddr
            FeEx fe = FeEx(scAddr);
            fe.eFeedback(msg.sender, _storageNode, string _transID);
        }
    }
}
```

Similarly, when a data owner gives feedback toward a
storage node (with value `fbScore`), DDS invokes `expCal`
function that calculates the experience relationship between
the two and updates `FeExInfo` accordingly. In the demon-
stration, feedback scores are randomly generated; however,
in the real-world scenarios, a function to measure DDS QoS
shall be implemented to correctly reflect the service quality.
As Solidity supports interactions between SCs deployed on
Ethereum platform, the proposed trust system is feasibly ac-
tualised as any DApps including DDS can be incorporated by
invoking public functions or accessing trust-related in-
formation from state variables defined in the SCs of the pro-
posed trust system.

Finally, to reinforce service quality for a client, the DDS
service queries `RepPosInfo`, `RepNegInfo` and `FeExInfo` stored at `FeEx` and `Rep` SCs, respectively, to receive reputation
and experience values related to this client. The DDS ser-
vice then aggregates this information for finalising trust val-
ues between the client and the storage nodes and provides
the most trustworthy counterparts to the client.

6. System Analysis and Discussion

The demonstration system presented in Section 5 is a
proof-of-concept of a universal decentralised trust system
which is incorporated into a BC infrastructure as an underly-
ing service for supporting DApps. This section investigates
and discusses on the practicality, performance, and security-
related aspects of the proposed trust system.

6.1. Feasibility and Performance Evaluation

Practically, a variety of factors should be taken into ac-
count when deploying the trust system into real-world us-
age. For instance, gas cost for SC execution in Ethereum
Virtual Machine is high as such SCs requires high volume
storage for the state variables, as well as numerous oper-
ations and local variable manipulations in `FeEx` SC and the
cost for using `Oraclize` service in `Rep` SC. This calls for fur-
ther research on SC optimisation [11] and better off-chain
storage and calculation solutions.

As most of SCs, including `FeEx` and `Rep` SCs, are ded-
icated to performing critical tasks with minimal storage and
computation, the performance of a DApp is heavily depen-
dent on the BC platform but not the application built on top.
At present, permissionless BC platforms offer limited per-
formance in terms of both throughput and/or scalability. For
instance, Bitcoin and Ethereum main-net only handle about
7 and 15 transactions per second. In order to illustrate the
real-world performance, we deploy our system to differ-
ent BC platforms, i.e., Ethereum test-nets namely `Ropsten`,
`Kovan`, `Rinkeby`, and `Goerli`. We carry out latency measure-
ment of both `READ` and `WRITE` transactions to the ledger
`FeExInfo` in the `FeEx` SC in the four test-nets. The results
are shown in Fig. 8. The performance measurement script
can also be found at the same repo.\(^{15}\)

It is worth noting that in `READ` transactions, an Ethereum
platform does not perform the consensus mechanism; in-
stead, in `WRITE` transactions, consensus mechanism (i.e.,
Proof-of-Work (Ethash) in `Ropsten`, Proof of Authority (Au-
thority Round) in `Kovan`, Proof of Authority (Clique) in both

\(^{15}\)https://blog.blockchain.info/charts/n-transactions

\(^{16}\)https://github.com/nguyentb/Decentralised_Trust_Eth_IPFS/tree/
master/packages/performanceAnalysis

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Ropsten, and Goerli) is carried out as the state of the ledger is changed. In details, WRITE transactions require further complicated processes including block formulation and mining, broadcast the mined block to peers in the network, block verification, and updating the ledger. This is why the latency of READ transactions is much smaller than WRITE transactions, reassured by the results in Fig. 8. As can be seen in the figure, the average latency of READ transactions is roughly the same in all four test-nets at around 350-420 ms with relatively small standard deviations. This indicates the consistency when querying data from the ledger. Compared to READ transactions, the average latency in WRITE transactions is significantly risen to 6013, 10376, 16973, and 17727 ms, which is 15 to 42 times higher, in Kovan, Rinkeby, Goerli, and Ropsten, respectively. The standard deviations, however, are different in the four test-nets: Ropsten and Goerli introduce considerably higher WRITE latency compared to Kovan and Rinkeby (2 – 3 times) but WRITE transactions are more stable as the standard deviations are small. Particularly, in Rinkeby test-net, the standard deviation is substantially high - The latency spreads out in a wide range, from 4500 to 17350 ms.

Results also show the block latency 17 in WRITE transactions in the four test-nets. In Kovan and Rinkeby, WRITE transactions are almost appended and confirmed in the next block demonstrated by block latency is close to 1 whereas in Goerli and Ropsten, it could take one or two more blocks before the transaction is written onto a new block. This is probably one of the reasons that the latency in Goerli and Ropsten is higher than in Kovan and Rinkeby.

Results of the system latency indicate the technical barrier on Ethereum-based system performance, which limits the usability of the proposed decentralised trust system to serve only small-scale services. Note that unlike the other test-nets, Ropsten performs Proof-of-Work consensus mechanism, similar with the Ethereum main-net, thus, it best reproduces the Ethereum production environment. Nevertheless, besides SC optimisation for individual DApps, system performance immensely relies on an underlying BC network which requires further research on consensus mechanisms [40], off-chain [26] and sharding solutions [39], etc. for a better DApp ecosystem.

6.2. System Security

The advanced capability of BC platform plays a key role in providing a secure and trustworthy environment for DApps. Although current BC and SC technologies still pose both performance limitations and security threats, we assume that the decentralised nature of the BC ensures there is no adversary can corrupt the BC network and change the content of the ledgers as this would imply majority of the network’s resources are compromised. Besides, there is no adversary who can impersonate another entity as the public-key cryptography (e.g., Elliptic Curve Digital Signature Algorithm (ECDSA) used in Ethereum) cannot be forged.

Security threats in our proposed decentralised trust system are from typical reputation-related attacks such as Self-promoting, Slandering (good/bad mouthing), and Whitewashing [16]. In our system, in order to be able to provide feedback, entity is required to make a transaction toward the counterpart, which costs some fee, at least transaction fee. Importantly, the proposed reputation mechanism itself can mitigate such reputation attacks. For instance, if a newly-created entity (thus its reputation value is minimal), makes a transaction, and then gives bad/good feedback toward a victim; the contribution of this feedback to the reputation value of the victim is minimal. This is because the reputation value of the victim is calculated based on both experience and reputation score of participants who transact with the victim (indicated in Equation (6) and (7) ). Obviously, if an entity is high-reputed (thus, probably not malicious) then the contribution (to one’s reputation) is huge. Generally, our reputation mechanism shares the same characteristics to Page-rank algorithm in Google web-ranking engine: it is not easy to increase the ranking of a web-page by creating lots of new web-pages and link to it [4]. The nature of any feedback-based reputation systems is that it is impossible to fully prevent from such reputation attacks; however, we believe our approach can well mitigate these behaviours.

7. Conclusion

In this paper, we have provided a comprehensive concept, system model and design of a decentralised trust system for DApps ecosystem along with detailed analysis, algorithms, and simulations actualise the DER trust model. Foremost, we have developed a proof-of-concept system implementing the DER trust model on top of the Ethereum permissionless BC. The trust system is then able to incorporate with the DDS service for supporting data owners to select trustworthy storage nodes.

We have also provided technical difficulties along with prospective solutions as well as the implementation refer-
ence in the development of the proposed decentralised trust system. Existing technical barriers are also outlined which need further efforts to be successfully solved. We believe our research significantly contributes to further activities on trust-related research areas and open some future research directions to strengthen a trustworthy DApp ecosystem.

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References

[1] Ali, M., Nelson, J., Shea, R., Freedman, M.J., 2016. Blockstack: A global naming and storage system secured by blockchains, in: {USENIX} Annual Technical Conference, pp. 181–194.

[2] Almenárez, F., Marín, A., Díaz, D., Cortés, A., Campo, C., García-Rubio, C., 2011. Trust management for multimedia p2p applications in autonomic networking. Ad Hoc Networks 9, 687–697.

[3] Arasu, A., Novak, J., Tomkins, A., Tomlin, J., 2002. Pagerank computation and the structure of the web: Experiments and algorithms, in: Proceedings of the Eleventh International World Wide Web Conference, Poster track, pp. 107–117.

[4] Avrachenkov, K., Litvak, N., 2006. The effect of new links on google pagerank. Stochastic Models 22, 319–331.

[5] Blum, A., Chan, T.H., Rwehbangira, M.R., 2006. A random-surfer web-graph model, in: 2006 Proceedings of the Third Workshop on Analytic Algorithmics and Combinatorics (ANALCO), SIAM, pp. 238–246.

[6] Bonomi, F., Milito, R., Zhu, J., Addepalli, S., 2012. Fog computing and its role in the internet of things, in: Proceedings of the first edition of the MCC workshop on Mobile cloud computing, pp. 13–16.

[7] Brin, S., Page, L., 2012. Reprint of: The anatomy of a large-scale hypertextual web search engine. Computer networks 56, 3825–3833.

[8] Buterin, V., 2014. Daos, dacs, das and more: An incomplete terminology guide. Ethereum Blog 6, 2014.

[9] Buterin, V., et al., 2014. A next-generation smart contract and decen- tralized application platform. white paper 3.

[10] Chebolu, P., Melsted, P., 2008. Pagerank and the random surfer model, in: SODA, pp. 1010–1018.

[11] Chen, T., Li, X., Luo, X., Zhang, X., 2017. Under-optimized smart contracts devour your money, in: 2017 IEEE 24th International Conference on Software Analysis, Evolution and Reengineering (SANER), IEEE, pp. 442–446.

[12] Chen, X., Ding, J., Lu, Z., 2020. A decentralized trust management system for intelligent transportation environments. IEEE Transactions on Intelligent Transportation Systems.

[13] Debe, M., Salah, K., Rehman, M.H.U., Svetinovic, D., 2019. Iot public fog nodes reputation system: A decentralized solution using ethereum blockchain. IEEE Access 7, 178082–178093.

[14] Hackius, N., Petersen, M., 2017. Blockchain in logistics and supply chain: trick or treat?, in: Proceedings of the Hamburg International Conference of Logistics (HICL), epubli, pp. 3–18.

[15] Haveliwala, T., Kamvar, S., Jeh, G., 2003. An analytical comparison of approaches to personalizing pagerank. Technical Report. Stanford.

[16] Hoffman, K., Zage, D., Nita-Rotaru, C., 2009. A survey of attack and defense techniques for reputation systems. ACM Computing Surveys (CSUR) 42, 1–31.

[17] Jawaheer, G., WELLER, P., Kostkova, P., 2014. Modeling user preferences in recommender systems: A classification framework for explicit and implicit user feedback. ACM Transactions on Interactive Intelligent Systems (TiiS) 4, 1–26.

[18] Johnston, D., Yilmaz, S.O., Kandah, J., Bentenitis, N., Hashemi, F., Gross, R., Wilkinson, S., Mason, S., 2014. The general theory of decentralized applications - dapps.

[19] Kamvar, S.D., Haveliwala, T.H., Manning, C.D., Golub, G.H., 2003. Extrapolation methods for accelerating pagerank computations, in: Proceedings of the 12th international conference on World Wide Web, pp. 261–270.

[20] Kochovski, P., Gec, S., Stankovski, V., Bajec, M., Drobinsev, P.D., 2019. Trust management in a blockchain based fog computing platform with trustless smart oracles. Future Generation Computer Systems 101, 747–759.

[21] Korpela, K., Hallikas, J., Dahlberg, T., 2017. Digital supply chain transformation toward blockchain integration, in: proceedings of the 50th Hawaii international conference on system sciences.

[22] Li, R., Song, T., Mei, B., Li, H., Cheng, X., Sun, L., 2018. Blockchain for large-scale internet of things data storage and protection. IEEE Transactions on Services Computing.

[23] Meiklejohn, S., Pomarole, M., Jordan, G., Levechenko, K., McCoy, D., Voelker, G.M., Savage, S., 2013. A fistful of bitcoins: characterizing payments among men with no names, in: Proceedings of the 2013 conference on Internet measurement conference, pp. 127–140.

[24] Moinet, A., Darties, B., Baril, J.L., 2017. Blockchain based trust & authentication for decentralized sensor networks. arXiv preprint arXiv:1706.01730.

[25] Page, L., Brin, S., Motwani, R., Winograd, T., 1999. The PageRank citation ranking: Bringing order to the web. Technical Report. Stanford InfoLab.

[26] Poon, J., Drijia, T., 2016. The bitcoin lightning network: Scalable off-chain instant payments.

[27] Roberts, S.G., Dunbar, R.I., Pollet, T.V., Kuppens, T., 2009. Exploring variation in active network size: Constraints and ego characteristics. Social Networks 31, 138–146.

[28] Shafagh, H., Burkalter, L., Hithnawi, A., Duquennoy, S., 2017. Towards blockchain-based auditable storage and sharing of iot data, in: Proceedings of the 2017 on Cloud Computing Security Workshop, ACM, pp. 45–50.

[29] She, W., Liu, Q., Tian, Z., Chen, J.S., Wang, B., Liu, W., 2019. Blockchain trust model for malicious node detection in wireless sensor networks. IEEE Access 7, 38947–38956.

[30] Truong, N.B., Lee, G.M., Um, T.W., Mackay, M., 2019. Trust evaluation mechanism for user recruitment in mobile crowd-sensing in the internet of things. IEEE Transactions on Information Forensics and Security 14, 2705–2719.

[31] Truong, N.B., Um, T.W., Zhou, B., Lee, G.M., 2017. From personal experience to global reputation for trust evaluation in the social internet of things, in: GLOBECOM 2017-2017 IEEE Global Communications Conference, IEEE, pp. 1–7.

[32] Truong, N.B., Um, T.W., Zhou, B., Lee, G.M., 2018. Strengthening the blockchain-based internet of value with trust, in: 2018 IEEE International Conference on Communications (ICC), IEEE, pp. 1–7.

[33] Tyagi, N., Sharma, S., 2012. Weighted page rank algorithm based on number of visits of links of web page. International Journal of Soft Computing and Engineering (IJSCE) ISSN , 2231–2307.

[34] Urena, R., Kou, G., Dong, Y., Chiclana, F., Herrera-Viedma, E., 2019. A review on trust propagation and opinion dynamics in social networks and group decision making frameworks. Information Sciences 478, 461–475.

[35] Xing, W., Ghorbani, A., 2004. Weighted pagerank algorithm, in: Proceedings, Second Annual Conference on Communication Networks and Services Research, 2004., IEEE, pp. 305–314.

[36] Xu, X., Poutasso, C., Zhu, L., Gramoli, V., Ponomarev, A., Tran, A.B., Chen, S., 2016. The blockchain as a software connector, in: 2016 13th Working IEEE/IFIP Conference on Software Architecture (WICSIA), IEEE, pp. 182–191.

[37] Yan, Z., Zhang, P., Vasilakos, A.V., 2014. A survey on trust management for internet of things. Journal of network and computer applications Conference, IEEE. pp. 1–7.

[38] Yang, Z., Yang, K., Lei, L., Zheng, K., Leung, V.C., 2018. Trust evaluation for large-scale internet of things data storage and protection. IEEE Transactions on Services Computing.
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Blockchain-based decentralized trust management in vehicular networks. IEEE Internet of Things Journal 6, 1495–1505.

[39] Zamani, M., Movahedi, M., Raykova, M., 2018. Rapidchain: Scaling blockchain via full sharding, in: Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security, pp. 931–948.

[40] Zheng, Z., Xie, S., Dai, H., Chen, X., Wang, H., 2017. An overview of blockchain technology: Architecture, consensus, and future trends, in: 2017 IEEE international congress on big data (BigData congress), IEEE, pp. 557–564.

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