

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Título da Dissertação

Nome do Autor

VERSÃO DE TRABALHO



FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Mestrado Integrado em Engenharia Informática e Computação

Orientador: Nome do Orientador

1 de Abril de 2019

Título da Dissertação

Nome do Autor

Mestrado Integrado em Engenharia Informática e Computação

Resumo

O Resumo fornece ao leitor um sumário do conteúdo da dissertação. Deverá ser breve mas conter detalhe suficiente e, uma vez que é a porta de entrada para a dissertação, deverá dar ao leitor uma boa impressão inicial.

Este texto inicial da dissertação é escrito no fim e resume numa página, sem referências externas, o tema e o contexto do trabalho, a motivação e os objectivos, as metodologias e técnicas empregues, os principais resultados alcançados e as conclusões.

Este documento ilustra o formato a usar em dissertações na Faculdade de Engenharia da Universidade do Porto. São dados exemplos de margens, cabeçalhos, títulos, paginação, estilos de índices, etc. São ainda dados exemplos de formatação de citações, figuras e tabelas, equações, referências cruzadas, lista de referências e índices. É usado texto descartável, *Loren Ipsum*, para preencher a dissertação por forma a ilustrar os formatos.

Seguem-se umas notas breves mas muito importantes sobre a versão provisória e a versão final do documento. A versão provisória, depois de verificada pelo orientador e de corrigida em contexto pelo autor, deve ser publicada na página pessoal de cada estudante/dissertação, juntamente com os dois resumos, em português e em inglês; deve manter a marca da água, assim como a numeração de linhas conforme aqui se demonstra.

A versão definitiva, a produzir somente após a defesa, em versão impressa (dois exemplares com capas próprias FEUP) e em versão eletrónica (6 CDs com "rodela" própria FEUP), deve ser limpa da marca de água e da numeração de linhas e deve conter a identificação, na primeira página, dos elementos do júri respetivo. Deve ainda, se for o caso, ser corrigida de acordo com as instruções recebidas dos elementos júri.

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vehicula lorem commodo dui. Fusce mollis feugiat elit. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Donec eu quam. Aenean consectetur odio quis nisi. Fusce molestie metus sed neque. Praesent nulla. Donec quis urna. Pellentesque hendrerit vulputate nunc. Donec id eros et leo ullamcorper placerat. Curabitur aliquam tellus et diam.

Ut tortor. Morbi eget elit. Maecenas nec risus. Sed ultricies. Sed scelerisque libero faucibus sem. Nullam molestie leo quis tellus. Donec ipsum. Nulla lobortis purus pharetra turpis. Nulla laoreet, arcu nec hendrerit vulputate, tortor elit eleifend turpis, et aliquam leo metus in dolor. Praesent sed nulla. Mauris ac augue. Cras ac orci. Etiam sed urna eget nulla sodales venenatis. Donec faucibus ante eget dui. Nam magna. Suspendisse sollicitudin est et mi.

Phasellus ullamcorper justo id risus. Nunc in leo. Mauris auctor lectus vitae est lacinia egestas. Nulla faucibus erat sit amet lectus varius semper. Praesent ultrices vehicula orci. Nam at metus. Aenean eget lorem nec purus feugiat molestie. Phasellus fringilla nulla ac risus. Aliquam elementum aliquam velit. Aenean nunc odio, lobortis id, dictum et, rutrum ac, ipsum.

Ut tortor. Morbi eget elit. Maecenas nec risus. Sed ultricies. Sed scelerisque libero faucibus sem. Nullam molestie leo quis tellus. Donec ipsum.

Abstract

Here goes the abstract written in English.

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vehicula lorem commodo dui. Fusce mollis feugiat elit. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Donec eu quam. Aenean consectetur odio quis nisi. Fusce molestie metus sed neque. Praesent nulla. Donec quis urna. Pellentesque hendrerit vulputate nunc. Donec id eros et leo ullamcorper placerat. Curabitur aliquam tellus et diam.

Ut tortor. Morbi eget elit. Maecenas nec risus. Sed ultricies. Sed scelerisque libero faucibus sem. Nullam molestie leo quis tellus. Donec ipsum. Nulla lobortis purus pharetra turpis. Nulla laoreet, arcu nec hendrerit vulputate, tortor elit eleifend turpis, et aliquam leo metus in dolor. Praesent sed nulla. Mauris ac augue. Cras ac orci. Etiam sed urna eget nulla sodales venenatis. Donec faucibus ante eget dui. Nam magna. Suspendisse sollicitudin est et mi.

Fusce sed ipsum vel velit imperdiet dictum. Sed nisi purus, dapibus ut, iaculis ac, placerat id, purus. Integer aliquet elementum libero. Phasellus facilisis leo eget elit. Nullam nisi magna, ornare at, aliquet et, porta id, odio. Sed volutpat tellus consectetur ligula. Phasellus turpis augue, malesuada et, placerat fringilla, ornare nec, eros. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos himenaeos. Vivamus ornare quam nec sem mattis vulputate. Nullam porta, diam nec porta mollis, orci leo condimentum sapien, quis venenatis mi dolor a metus. Nullam mollis. Aenean metus massa, pellentesque sit amet, sagittis eget, tincidunt in, arcu. Vestibulum porta laoreet tortor. Nullam mollis elit nec justo. In nulla ligula, pellentesque sit amet, consequat sed, faucibus id, velit. Fusce purus. Quisque sagittis urna at quam. Ut eu lacus. Maecenas tortor nibh, ultricies nec, vestibulum varius, egestas id, sapien.

Phasellus ullamcorper justo id risus. Nunc in leo. Mauris auctor lectus vitae est lacinia egestas. Nulla faucibus erat sit amet lectus varius semper. Praesent ultrices vehicula orci. Nam at metus. Aenean eget lorem nec purus feugiat molestie. Phasellus fringilla nulla ac risus. Aliquam elementum aliquam velit. Aenean nunc odio, lobortis id, dictum et, rutrum ac, ipsum.

Ut tortor. Morbi eget elit. Maecenas nec risus. Sed ultricies. Sed scelerisque libero faucibus sem. Nullam molestie leo quis tellus. Donec ipsum. Nulla lobortis purus pharetra turpis. Nulla laoreet, arcu nec hendrerit vulputate, tortor elit eleifend turpis, et aliquam leo metus in dolor. Praesent sed nulla. Mauris ac augue. Cras ac orci. Etiam sed urna eget nulla sodales venenatis. Donec faucibus ante eget dui. Nam magna. Suspendisse sollicitudin est et mi.

Phasellus ullamcorper justo id risus. Nunc in leo. Mauris auctor lectus vitae est lacinia egestas. Nulla faucibus erat sit amet lectus varius semper. Praesent ultrices vehicula orci. Nam at metus. Aenean eget lorem nec purus feugiat molestie. Phasellus fringilla nulla ac risus. Aliquam elementum aliquam velit. Aenean nunc odio, lobortis id, dictum et, rutrum ac, ipsum.

Ut tortor. Morbi eget elit. Maecenas nec risus. Sed ultricies. Sed scelerisque libero faucibus sem. Nullam molestie leo quis tellus. Donec ipsum.

Agradecimentos

Aliquam id dui. Nulla facilisi. Nullam ligula nunc, viverra a, iaculis at, faucibus quis, sapien. Cum sociis natoque penatibus et magnis dis parturient montes, nascetur ridiculus mus. Curabitur magna ligula, ornare luctus, aliquam non, aliquet at, tortor. Donec iaculis nulla sed eros. Sed felis. Nam lobortis libero. Pellentesque odio. Suspendisse potenti. Morbi imperdiet rhoncus magna. Morbi vestibulum interdum turpis. Pellentesque varius. Morbi nulla urna, euismod in, molestie ac, placerat in, orci.

Ut convallis. Suspendisse luctus pharetra sem. Sed sit amet mi in diam luctus suscipit. Nulla facilisi. Integer commodo, turpis et semper auctor, nisl ligula vestibulum erat, sed tempor lacus nibh at turpis. Quisque vestibulum pulvinar justo. Class aptent taciti sociosqu ad litora torquent per conubia nostra, per inceptos himenaeos. Nam sed tellus vel tortor hendrerit pulvinar. Phasellus eleifend, augue at mattis tincidunt, lorem lorem sodales arcu, id volutpat risus est id neque. Phasellus egestas ante. Nam porttitor justo sit amet urna. Suspendisse ligula nunc, mollis ac, elementum non, venenatis ut, mauris. Mauris augue risus, tempus scelerisque, rutrum quis, hendrerit at, nunc. Nulla posuere porta orci. Nulla dui.

Fusce gravida placerat sem. Aenean ipsum diam, pharetra vitae, ornare et, semper sit amet, nibh. Nam id tellus. Etiam ultrices. Praesent gravida. Aliquam nec sapien. Morbi sagittis vulputate dolor. Donec sapien lorem, laoreet egestas, pellentesque euismod, porta at, sapien. Integer vitae lacus id dui convallis blandit. Mauris non sem. Integer in velit eget lorem scelerisque vehicula. Etiam tincidunt turpis ac nunc. Pellentesque a justo. Mauris faucibus quam id eros. Cras pharetra. Fusce rutrum vulputate lorem. Cras pretium magna in nisl. Integer ornare dui non pede.

O Nome do Autor

“If I have seen further it is by standing on ye sholders of Giants.”

Isaac Newton

Conteúdo

1	Introduction	1
1.1	Blockchain	1
1.2	Smart Contracts	2
1.3	The smart contract connectivity problem	2
1.4	Smart contracts space and computation limits	3
1.5	Oracles as a solution	4
1.6	Oracles trust	4
1.7	Motivation and Objectives	4
1.8	Document Structure	5
2	State of the art	7
2.1	Research	7
2.1.1	Research Questions	7
2.1.2	Review strategy and data sources	7
2.1.3	Study Selection and Quality assessment	9
2.1.4	Results	10
2.2	Non-Academia Research	12
2.2.1	Findings	12
2.3	Summary and conclusions	12
2.3.1	Conclusions	13
3	Trustable Oracles	15
3.1	Defining Trust	15
3.2	Oracle Architectures	16
3.2.1	Oracle as a Service w/ Single Data Feed.	16
3.2.2	Oracle as a Service w/ Multiple Data Feeds.	20
3.2.3	Single-Party Self Hosted Oracle.	20
3.2.4	Multi-Party Self Hosted Oracle.	20
3.3	Summary and conclusions	20
4	Implementation	23
4.1	Summary and conclusions	23
5	Conclusions and Future Work	25
	Referências	27
A		29

CONTEÚDO

Lista de Figuras

1.1	Smart contract connectivity problem.	3
1.2	Oracle integration.	5
2.1	Review strategy.	8
2.2	Screening stages.	10
3.1	Oracle as a Service w/ Single Data Feed.	17
3.2	Oracle as a Service w/ Multiple Data Feeds.	19
3.3	Single-Party Self Hosted Oracle.	21
3.4	Multi-Party Self Hosted Oracle.	22

LISTA DE FIGURAS

Lista de Tabelas

2.1	Search results per database	9
2.2	Search results per year	9
2.3	Summary of oracle projects/research.	13

LISTA DE TABELAS

Abreviaturas e Símbolos

ADT	Abstract Data Type
ANDF	Architecture-Neutral Distribution Format
API	Application Programming Interface
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CORBA	Common Object Request Broker Architecture
UNCOL	UNiversal CCompiler-oriented Language
Loren	Lorem ipsum dolor sit amet, consectetur adipiscing elit. Sed vehicula lorem commodo dui
WWW	<i>World Wide Web</i>

Capítulo 1

Introduction

Once more, a technological revolution sparked in a not-yet-ready world. Just as the Internet invention brought us closer together and opened an unlimited virtual world of possibilities so does blockchain. The technology is still in its early development days and many different proposals are being worked on as to improve its performance and scalability. Akin to the dot-com boom, a plethora of blockchain projects live on more expectations than results but ultimately blockchain could resolve the Internet's failed promise. To understand what is blockchain and why it is necessary we need to comprehend the social background around the time of its release. The Internet promised of a peer-to-peer connected world, however, financial incentives and technological challenges led to a centralized and non-privacy advocated virtual world. The increasing general concern regarding privacy of personal information and the meddling of third parties in everyday online actions allied with the financial crash of 2008 lead to a new technological and social breakthrough.

Satoshi Nakamoto's introduced Bitcoin, in 2009 [Nak09], and revolutionized money and currency, setting the first example of a digital asset which has no backing or intrinsic value and more importantly no centralized issuer or controller. In order to require no third party to verify each transaction and prevent double-spending, he introduced a distributed ledger mechanism now known as Blockchain.

1.1 Blockchain

Blockchain is a tool for distributed consensus, in a byzantine fault-tolerant approach, without requiring to trust in centralized parties. In this ledger, transactions are recorded in an ongoing chain, creating an immutable public record that cannot be changed without redoing the proof-of-work. Anyone can become a node and leave and rejoin the network. Having incentives to work on the CPU intensive proof-of-work, extending the chain, and so, for as long as the majority of nodes are trustworthy, the longest and honest chain will thrive. The proof-of-work used on

Bitcoin is HashCash, proposed in 1997 by Adam Back, is a cryptographic hash-based proof-of-work algorithm that requires a selectable amount of work to compute, but the proof can be verified efficiently. Nodes can easily verify that a block is valid and that some effort was put in its creation. The proof-of-work difficulty can increase and decrease depending on the network size and capability, creating on average a block every 10 minutes, like an heartbeat.

In simpler terms, transactions are grouped in blocks and for each block there is a mathematical challenge (proof-of-work) which requires time and computational resources to be solved, guaranteeing that some effort is put into solving the challenge and therefore making it extremely hard to quickly manufacture false blocks. Each block has an hash, a signature, of the previous block linking all blocks in a single chain. Nodes always work on the longest chain, so as long as the majority of the nodes are honest and work in building correct blocks, which means they don't have double entries and transactions are legitimate, the biggest chain will grow and remain a trusted and distributed ledger.

Leveraging Blockchain, Bitcoin requires no personal information to exchange value, anyone can join the network and no central authority is needed. This opens an unlimited world of new scenarios for the use of blockchain.

1.2 Smart Contracts

In 2015, Ethereum was launched as an alternative protocol for building decentralized applications called smart contracts. Introduced as applications that run on the blockchain, smart contracts are self-verifying, self-executing and immutable contracts whose terms are directly written in lines of code which persist on the blockchain, promising to replace real world contracts. Contracts are the building blocks of our identity, economy and society. They enforce agreements between multiple parties and ensure trust in the compliance of the rules of the agreement but traditional contracts lack on automation and decentralization. Smart Contracts provide the ability to execute tamper-proof digital agreements, which are considered highly secure and highly reliable.

Smart contracts have a wide range of use cases. For example, they can be used in Supply Chains and Logistics. Smart contracts allow tracking product movement from the factory to the store shelves. Each intermediary signs a step of the contract which then the final consumer can analyse and have the guarantee of the origin of the product. <

1.3 The smart contract connectivity problem

The Ethereum blockchain is designed to be entirely deterministic [Gav14], meaning that if someone downloads the whole network history and replays it they should always end up with the same state. Bearing this in mind, smart contracts cannot directly query URLs for a certain information since everyone must be able to independently validate the outcome of running a given contract making it impossible to guarantee that everyone would retrieve the same information since the internet is non-deterministic and changes over time. Determinism is necessary so that

Introduction



Figura 1.1: Smart contract connectivity problem.

nodes can come to a consensus. In order for smart contracts to gain traction they need access information of the real world, outside of the blockchain. For example, the current price of the US dollar. However smart contracts cannot directly query the internet for information due to the non-deterministic nature of the internet. Meaning that the information retrieved at some point in time cannot be entrusted to be available or equal in another point in the future, which may result in different states when validating smart contracts by querying the internet in different moments. Oracles solve the non-deterministic problem, of querying the internet, by inputting external information on the blockchain through a transaction making sure that the blockchain contains all the information required to verify itself.

1.4 Smart contracts space and computation limits

Another problem for smart contracts is performing long and costly operations in terms of computation and space. Several platforms are implementing smart contracts, also called DAPPs, Distributed Applications, namely Ethereum and EOS, among others.

On the Ethereum platform, smart contracts pay "Gas" to run. "Gas" is a unit that measures the amount of computation effort that certain operations require to execute. "Gas" is basically the fees paid to the network in order to execute an operation. Therefore, the longer the application runs the more "Gas" the smart contract has to pay.

EOS, on the opposite of Ethereum, works on an ownership model whereby users own and are entitled to use of resources in proportion to their stake. Basically, instead of paying transaction fees, the owner who holds N tokens is entitled to $N \cdot k$ transactions. While Ethereum rents out computational power on the network, EOS gives ownership of the resources in accordance to the amount of EOS held. The mentioned resources are RAM, corresponding to the used state on the network, CPU measuring the average consumption of computing resources and NET which measures used bandwidth. With increasing prices of EOS tokens, staking these resources becomes very costly.

All in all, either for users of smart contracts or the teams deploying them, keeping smart contracts efficient and performing non-costly operation is the key. Nonetheless, sometimes applications require costly operations and outsourcing them to an oracle outside of the blockchain is the answer.

1.5 Oracles as a solution

The solution to the smart contract connectivity problem and to outsourcing computation from the blockchain is the use of a secure blockchain middle-ware, mentioned before as, an oracle. Oracles can query data from APIs, datafeeds, other blockchains or perform their own calculations and input that data on the smart contract. This way the blockchain has all the necessary information to verify the result of running a smart contract, and will always produce the same result, independently of the point in time in which that verification is ran.

1.6 Oracles trust

Trust in oracles comprises two main components, service availability, trusting that the service will always return a response to our query, and untampered relay of information, meaning the information the oracle computed or queried is original and not tampered with. If oracles are compromised we risk compromising the trust of the underlying blockchain by inputting falsified information in a system that is trusted to always have a valid state. Therefore it is imperative that oracles provide a proof for the information they provide, as well, as keep a decentralized approach by having a network of oracles always available to answer the queries.

1.7 Motivation and Objectives

The research hereby exposed was proposed by Takai, a blockchain start-up born in Porto, Portugal with the purpose to be the first blockchain open innovation platform. Sponsored by Bright Pixel, an innovation hub and venture investment house, who supports promising startups in their early years. Taikai is building a platform that connects talent and entrepreneurs with the challenges of the corporate players, through the power of the sharing economy and blockchain trust. Taikai's project will serve as proof-of-concept for the implementation of trustable oracles.

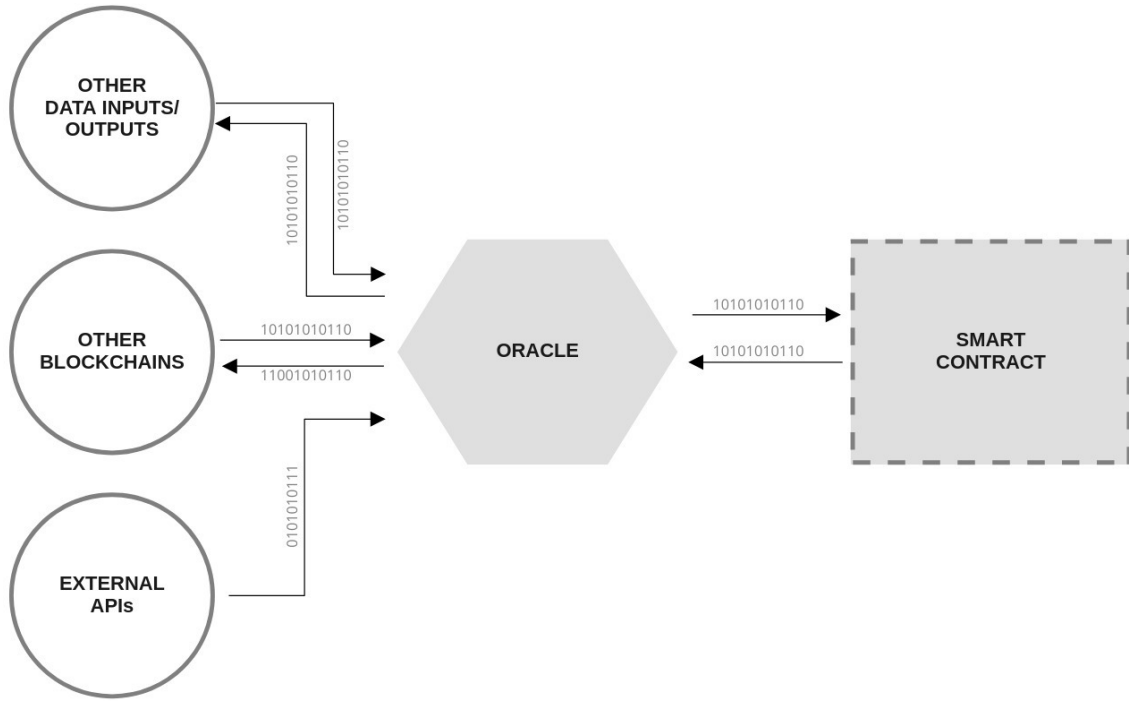


Figura 1.2: Oracle integration.

The growing interest in blockchain technology and specially in the potential of Smart Contracts together with the lack of research on trustable oracles creates a gap on the general adoption of blockchain by business and governments. This gap and the opportunity bestowed with the Taikai project provides the perfect context for pursuing the construction of a bridge to overcome the oracle trust problem and further empower existing and future blockchain projects.

The proposed objectives for this work are as follows:

- Identifying the necessary components for end-to-end reliability between smart contracts and outside blockchain information;
- Providing a general framework for guaranteeing oracle trust;
- Implementing a proof-of-concept in the Taikai project on the EOS blockchain;

1.8 Document Structure

Introduction

Capítulo 2

State of the art

The topic of blockchain oracles is still unexplored territory mostly investigated by start-up companies and individuals thriving to solve a new problem. Therefore, research related to oracles may not yet be documented on peer-reviewed papers but, nonetheless, is invaluable in an early phase of the technology. Consequently, the state of the art cannot be complete without reviewing the work developed by the academia and also by start-ups, enterprises, governments and individuals.

2.1 Research

In terms of academic research a systematic literature review was performed. It's main components and finding are described in this section. A literature review allows scholars not to step on each other's shoes but to climb on each other's shoulders [KKC07], meaning, not duplicating existing research and find the gaps and strive to discover something new. To conduct a non-biased, methodical and reproducible review, to the extent that a human can, it is necessary to clarify and identify at the beginning of the research its methodology, what are the data sources and what is the selection criteria.

2.1.1 Research Questions

First of all and to guide the focus of the research, the following research question was defined:

- RQ1: What kind of blockchain oracles have been proposed?

2.1.2 Review strategy and data sources

Figure 2.1, presents the predefined review strategy used in order to achieve such a goal and maintain unbiased, transparent and reproducible research.

The following 5 electronic databases were used to query for such information:

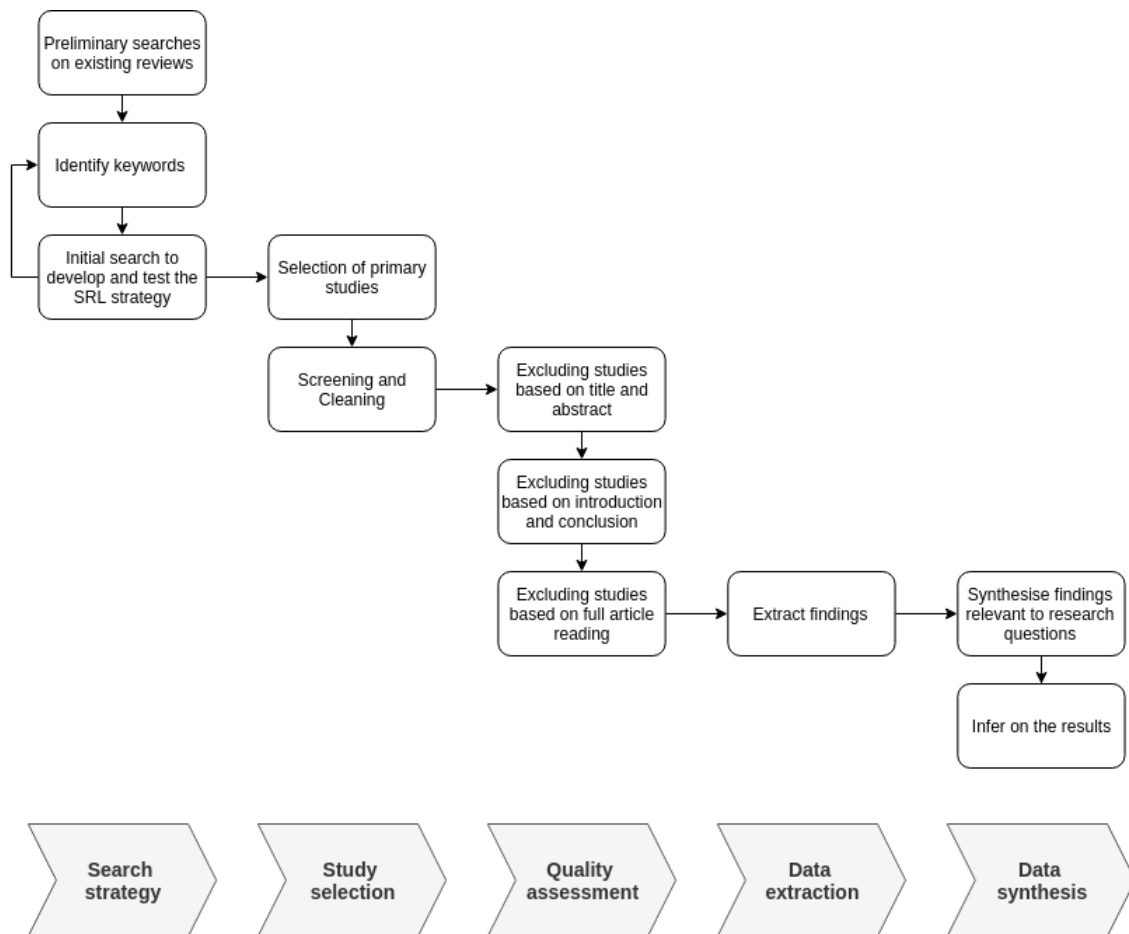


Figura 2.1: Review strategy.

- ACM Digital Library
- IEEE Xplore
- Scopus
- Google Scholar

The defined search query for the search of the relevant paper was the following:

((("blockchain"OR "block chain"OR "block-chain") AND ("oracles"OR "oracle"OR "middle-ware"OR "middleware"OR "middle ware"OR "datafeed"OR "data feed"OR "data-feed"))

The search was performed on the 5th of February 2019 and revealed the results presented in 2.1.

Database	Filters	Results
ACM Digital Library	Title, abstract and keywords	34
IEEE Xplore	Title, abstract and index terms	24
Scopus	Title, abstract and keywords	57
Google Scholar	Title	8
Total		123

Tabela 2.1: Search results per database

Since the concept of smart contracts on the blockchain was only introduced in 2015, with the introduction of the Ethereum blockchain, only results after 2015 were considered. Analysing the initial search results per year, in table 2.2, we can infer the growing popularity of oracle-related academic research. The year 2019 only comprises work done in the month of January since the search was performed in the beginning of February.



Tabela 2.2: Search results per year

2.1.3 Study Selection and Quality assessment

The study selection process initially started with a pool of 123 papers from the previously stated online databases. As described on figure 2.1, the selection compromised four stages:

- Stage 1: Screening and cleaning duplicated articles or articles that were not in English.
- Stage 2: Exclusion by carefully reading the title but most importantly the abstract. After this stage was finished, only 13 of the 123 papers were either describing specific trustable oracle implementations or mentioning the use of oracles.
- Stage 3: Analysing the introduction and conclusions in order to remove papers which do not describe a implementation of a trustable oracle or an protocol to overcome the trust in oracles.

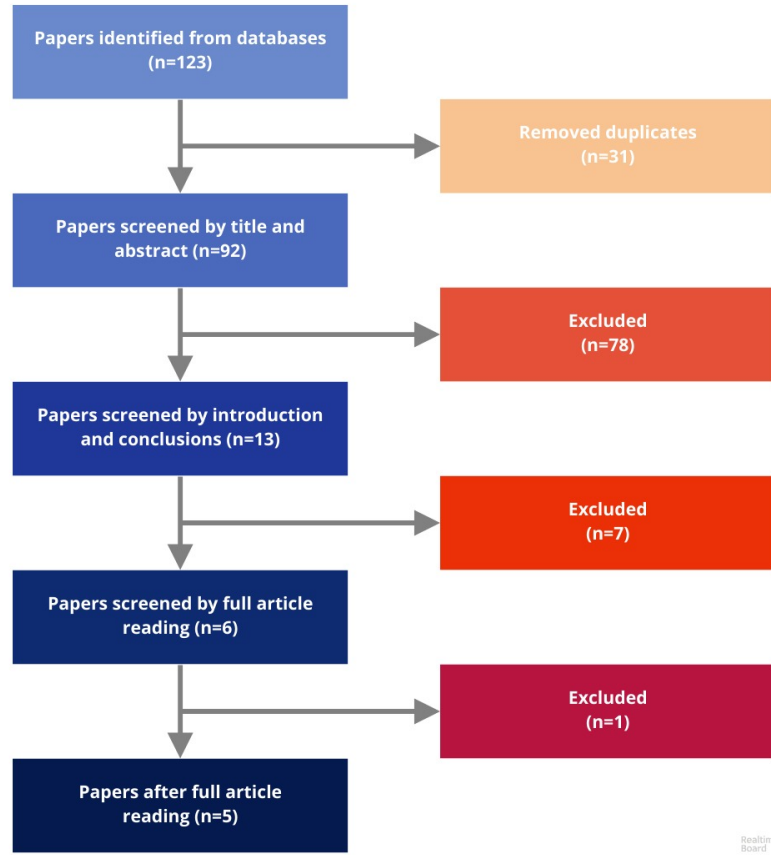


Figura 2.2: Screening stages.

- Stage 4: Full article reading to assess if the final bucket of articles answer the research questions.

2.1.4 Results

The following process resulted in three articles and two thesis that approach varying problems in implementing and guaranteeing trust in oracles.

Town Crier [ZCC⁺16], leverages trusted hardware, specifically Intel SGX, to scrape HTTPS-enabled websites and serve source-authenticated data to relaying smart contracts. TC architecture involves a TC contract on the blockchain that receives datagram requests from a User Contract on the blockchain and communicates those request to a TC server which then retrieves an answer from a data source through an HTTPS connection.

Astraea [ABV⁺18], proposes a decentralized oracle network with submitters, voters and certifiers, in which voters play a low-risk game and certifies a high-risk game with associated resources. Using game theory incentive structure as a means to keep the players honest.

[Gor17], proposes a protocol for oracle sensor data authenticity and integrity to an IoT devices network with low computational resources. Using sets of public and private keys to authenticate

that the oracle sensor data actually was originated by that oracle even if the information needs to pass by several oracles before being consumed by the application.

[MM18], defines a gambling protocol based on incentives and assuming that every entity involved has the objective to maximize their profit. The protocol overcomes the trust in a single Oracle by polling a network of 7 oracles from a large network of available oracles, they will then stake their money on a specific bet and only receive their investment back if the majority of the oracles vote in the same winner. Creating, therefore, incentives for Oracle good behaviour.

[EH18] does not propose a specific method but analyses existing solutions and defines a systematic classification for existing trustable off-chain computation oracles. The authors identifies the following off-chain computation oracles approaches:

- *Verifiable off-chain Computation*, a technique where a prover executes a computation and then publishes the result including a cryptographic proof attesting the computation's correctness to the blockchain. An on-chain verifier then verifies the proof and persists the result in case of success. Identified existing solutions are zkSNARKs, Bulletproofs and zkSTARKs. zkSNARKs require a setup phase which is more expensive than naive execution. After the setup, however, proof size and verification complexity are extremely small and independent of circuit complexity. This amortization makes zkSNARKs especially efficient for computations executed repeatedly, which is usually the case for off-chain state transitions. While zkSTARKs and Bulletproofs require no setup, proof size and verification complexity grow with circuit complexity, which limits applicability.
- *Secure Multiparty Computation*, SMPCs, enable a set of nodes to compute functions on secret data in a way that none of the nodes ever has access to the data in its entirety. Identifies Enigma, which proposes a privacy-preserving decentralized computation platform based on sMPCs where a blockchain stores a publicly verifiable audit trail. However, current sMPC protocols add too much overhead for such a network to be practical. Hence, Enigma now relies on Trusted Execution Environments
- *Enclave-based Computation*, relying on Trusted Execution Environments (TEE) to execute computations off-chain. Identified existing solutions are Enigma and Ekiden which present two different implementations of EOCs. In Enigma programs can either be executed on-chain or in enclaves that are distributed across a separate off-chain network. An Engima-specific scripting language allows developers to mark objects as private and hence, enforce off-chain computation. In contrast to Enigma, Ekiden does not allow on-chain computation but instead, the blockchain is solely used as persistent state storage.
- *Incentive-driven Off-chain Computation*, IOC, relies on incentive mechanisms applied to motivate off-chain computation and guarantee computational correctness. IOCs inherit two critical design issues: (1) Keep verifiers motivated to validate solutions and (2) reduce computational effort for the on-chain judge. The paper identifies TrueBit, as the first IOC implementation, proposing solutions for both challenges. As verifiers would stop validating

if solvers only published correct solutions, TrueBit enforces solvers to provide erroneous solutions from time to time and offers a reward to the verifiers for finding them.

2.2 Non-Academia Research

To search for non-academia research Google, a search engine and Medium, a platform for blog posting used widely by developers and the start-up community, were used as a means to find new projects or solutions for the oracle trust problem. Using these two tools a lot of projects were found trying to solve the oracle trust problem and are solely documented on white-papers or on the companies website documentation page.

2.2.1 Findings

The results of this search revealed a wide range of projects and protocols trying to achieve with varying degrees of decentralization or authenticity, a short explanation of each will be detailed here:

- Oraclize.it [Ora18], provides Authenticity Proofs for the data it fetches guaranteeing that the original data-source is genuine and untampered and can even make use of several data sources in order to gather trustable data, but its centralized model does not guarantee an always available service.
- ChainLink[EJN17], describes a decentralized network of oracles that can query multiple sources in order to avoid dependency of a sole oracle which can be prone to fail and also to gather knowledge from multiple sources to obtain a more reliable result. ChainLink is also considering implementing, in the future, authenticity proofs and make use of trusted hardware, as of now it requires users to trust in the ChainLink nodes to behave correctly.
- SchellingCoin protocol incentivizes a decentralized network of oracles to perform computation by rewarding participants who submit results that are closest to the median of all submitted results in a commit-reveal process.
- TrueBit, introduces a system of solvers and verifier. Solvers are compensated for performing computation and verifiers are compensated for detecting errors in solutions submitted by solvers.

2.3 Summary and conclusions

Summing up, this research highlighted two main types of oracles. The first is **Data-Carrier oracles**, whose main purpose is relaying query results from a trusted data source to a smart contract. The second is **Computation Oracles**, which not only relay query results, but also perform the relevant computation themselves. Computation oracles can be used as building blocks to construct off-chain computation markets. A summary on the results is described on table 2.3.

Author / Project	Type	Distributed Network	Achieves trust through
Town Crier	Data carrier	No	Trusted hardware signed attestations
Astraea	Data carrier	Yes	Game theory incentives
[Gor17]	Computation	Yes	Sets of public and private keys
[MM18]	Data carrier	Yes	Incentive based
TrueBit	Computation	Yes	Incentive based
Oraclize.it	Data carrier	No	TLSNotary
ChainLink	Data carrier	Yes	Query multiple sources
SchellingCoin	Computation	Yes	Incentive based

Tabela 2.3: Summary of oracle projects/research.

2.3.1 Conclusions

Two main conclusions come from both the academia and non-academia research.

The first of all, there is a clear lack of academia research on the topic of creating trustable oracles. Town Crier proposes a solution for relying data securely but requiring specific hardware. Astraea and [MM18] uses incentives and game theory as means for good oracle behaviour but doesn't not provide complete trust in edge cases in which pursuing erratic behaviour may be worth it. [EH18] is very promising in the field of Internet of Things for oracle sensor authentication but can only guarantee that data was generated by a specific sensor but the approach cannot be generalised for other oracle scenarios.

Secondly, even though the main research on trustable oracles is being pursued by startups or sole developers all the existing projects seem to be blockchain specific or in very early phases and not yet ready to be generally adopted.

The literature review points out the lack of research done by the academia in trying to solve one of the most important motives for blockchain general adoption. Only second, maybe, to scalability. The oracle trust problem, efficiently solved, opens doors to the contracts of the futures. Start-ups and sole developers are for now the main force in solving this problem which launches the challenge and motivation for the next chapter of this research.

State of the art

Capítulo 3

Trustable Oracles

3.1 Defining Trust

At this point, a definition of what trust in a oracle is seems appropriate. Trust has a lot of meanings, depending on the needs of all the parties involved. I will model several levels of trust and the requirements and fallacies of each model as well as its application and drawbacks.

Starting from an absolute trust scenario, in this model, the end user, being the smart contract which receives information provided by the oracle, has complete assurances from both the veracity of the data provided by the data-source, as well as, undeniable proof that the oracle did not tamper with the relayed information. This scenario points out two main points of failure, either maliciously or unintentionally.

The first component which can be faulty or compromised is the data-source. Assuring that the information provided is correct does not have a straightforward answer. What correct means is open to interpretation. For example, if the data source is an IoT sensor, which is prone to failures, being correct is relative. The sensor needs to be perfectly calibrated and accurate. In this case, using several sensors and averaging its values or removing outliers would solve its correctness. Another example, could be an API that returns the current value of the EUR in USD. In this scenario a party that would benefit from a higher conversion than the real one could coerce or attack the data-source into providing a favorable value. The answer here can also be using several data-sources. Another solution would be to use a highly trusted entity such as the European Central Bank (ECB) which can be a lot harder to coerce or attack and having a signatures from the ECB that backs the provided data. Choosing what type of data-source to use has a huge impact on the trust fullness of the provided data not to mention architecture centralization when using a source such as the ECB. All in all, the end user will have to understand the requirements and level of trust necessary.

The second, and most relevant for analysis, is the oracle service used. Oracles are a necessary part of the process, since the other option would be having the data providers adapting to the

blockchain which does not seem to be a realistic option at the moment. Therefore we must trust an oracle or a group of oracles. Two main options are available, either trusting a third-party oracle or self deploying an oracle. In the first scenario, three variables take part in the level of trust. Firstly the third-party oracle, if paid for, has the monetary incentive to be honest, since a bad record of dishonesty would have the service losing credibility and therefore clients. Secondly, by using proofs the oracle can establish its legitimacy, as long as, the proofs can undoubtedly be trusted and verifiable by the smart contract, I will later analyse in depth this issue. Finally, oracle execution transparency by using open-source code and having means for being audited. Additionally to guaranteeing single oracle integrity, it may be in the interest of the user to use several oracles either to provide service availability or to increase trust by combining the result from different oracle services.

3.2 Oracle Architectures

3.2.1 Oracle as a Service w/ Single Data Feed.

3.2.1.1 Context

Smart contracts will probably power a decentralized world of automation and trust-less commitments. Companies, groups and individuals will be able to automate tasks and contracts but as far as the ecosystem is, at the moment, smart contracts are limited to the information available in the blockchain. Therefore, connecting with the outside world requires a trusted authority to input in the blockchain the required information upon request from the smart contract. This trusted authority is generally called an oracle.

3.2.1.2 Example

3.2.1.3 Problem

As explained before, the deterministic nature of blockchain does not allow smart contracts to directly query a data-feed for information. In this context, oracles surge to empower business and smart contract capabilities, connecting smart contracts to the world outside of the blockchain. The problem here is to trust in the oracle service to not behave maliciously and undermine the trust provided by the blockchain consensus mechanisms. Blockchain technology can be trusted to behave correctly even in byzantine environments, but the oracle service does not abide by the same mechanisms and therefore must provide some kind of proof of honesty.

3.2.1.4 Forces

- **Smart contract empowerment** - Providing smart contracts with trustable information from outside of the blockchain is decisive to gain general adoption and practicality.

Trustable Oracles

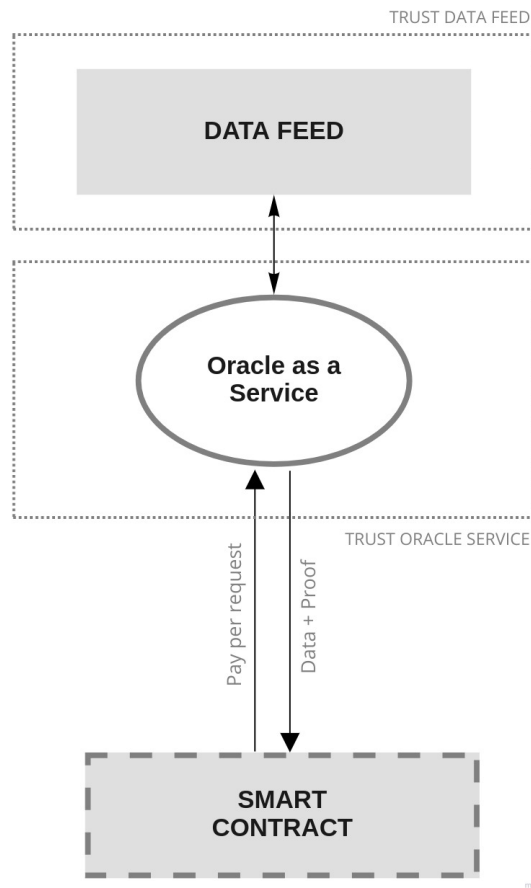


Figura 3.1: Oracle as a Service w/ Single Data Feed.

- **Blockchain Interoperability** - The ability to get information from other blockchains if possible using an oracle that queries one blockchain and inputs the information on another.
- **Keeping trust standards** - As blockchain technology creates a trust-less environment, oracles should as well keep up with the level of trust in their functioning.

3.2.1.5 Solution

A proposed and existing solution in the market is Oracles as a Service. Oraclize [Ora18] currently provides fee-based oracles in which smart contracts pay for each request. In order to achieve a higher level of trust, for an extra fee, it can also provide proofs that the provided data as not been tampered by their oracle. The extent to which this proofs can be trusted will be further analysed.

3.2.1.6 Example Resolved

3.2.1.7 Resulting Context

This solution results in an architecture that compromises two points of trust. The first being the data-feed itself. No guarantees are given that the data provided is reliable and the smart contract owner must therefore, to the best of his knowledge, select a data-feed in which, by the operator size or record of good behaviour, he can trust.

The second point of failure is the oracle service itself. Although smart contracts, in the resulting context, have access to the information from the outside, that is only possible due to the use of a third party to honestly relay the data. In this architecture, if the oracle simply relays the data, then no trust model can be achieved as the oracle good behavior is not tested against. As this would not be a feasible architecture the existing services provide authenticity proofs to guarantee, to a certain level, their honest behavior. The problem here is on how are these proofs generated, can they be verified on-chain or only off-chain and who is making, or providing, the verification tools. In chapter X I'll deep dive on these questions and techniques. Another reason to trust in the service can be the monetary incentive for good behavior. By paying the oracle for each request, that becomes the oracle service business model and therefore an extensive record of good behavior is crucial for business prosperity and therefore a good enough incentive for honestly conveying the requested data. In this context, if the authenticity proofs provide enough assurances for the smart contract creator and he trusts in the selected data-feed to provide the required data, then this model can satisfy its needs in terms of trust, as well as, performance, since it only queries one data-feed and uses only one oracle. By not having any consensus mechanism an exchange in the least amount of messages it can both achieve greater performance and a lower cost. But this lower cost and higher performance architecture by itself is prone to failure due to lack of decentralization and does not guarantee service availability which could lead to a failure in the smart contract to obtain the requested information.

Trustable Oracles



Figura 3.2: Oracle as a Service w/ Multiple Data Feeds.

3.2.1.8 Known Uses

3.2.2 Oracle as a Service w/ Multiple Data Feeds.

3.2.2.1 Context

3.2.2.2 Example

3.2.2.3 Problem

3.2.2.4 Forces

3.2.2.5 Solution

3.2.2.6 Example Resolved

3.2.2.7 Resulting Context

3.2.2.8 Known Uses

3.2.3 Single-Party Self Hosted Oracle.

3.2.3.1 Context

3.2.3.2 Example

3.2.3.3 Problem

3.2.3.4 Forces

3.2.3.5 Solution

3.2.3.6 Example Resolved

3.2.3.7 Resulting Context

3.2.3.8 Known Uses

3.2.4 Multi-Party Self Hosted Oracle.

3.2.4.1 Context

3.2.4.2 Example

3.2.4.3 Problem

3.2.4.4 Forces

3.2.4.5 Solution

3.2.4.6 Example Resolved

3.2.4.7 Resulting Context

3.2.4.8 Known Uses

3.3 Summary and conclusions

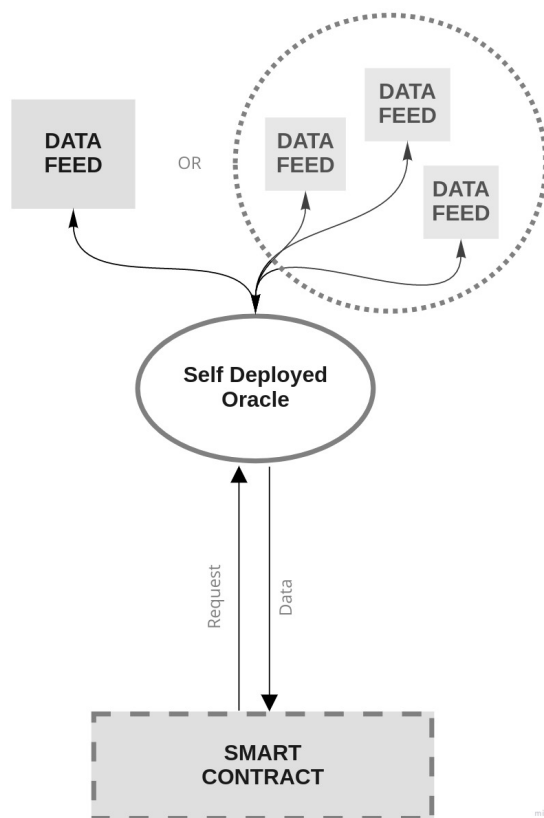


Figura 3.3: Single-Party Self Hosted Oracle.

Trustable Oracles

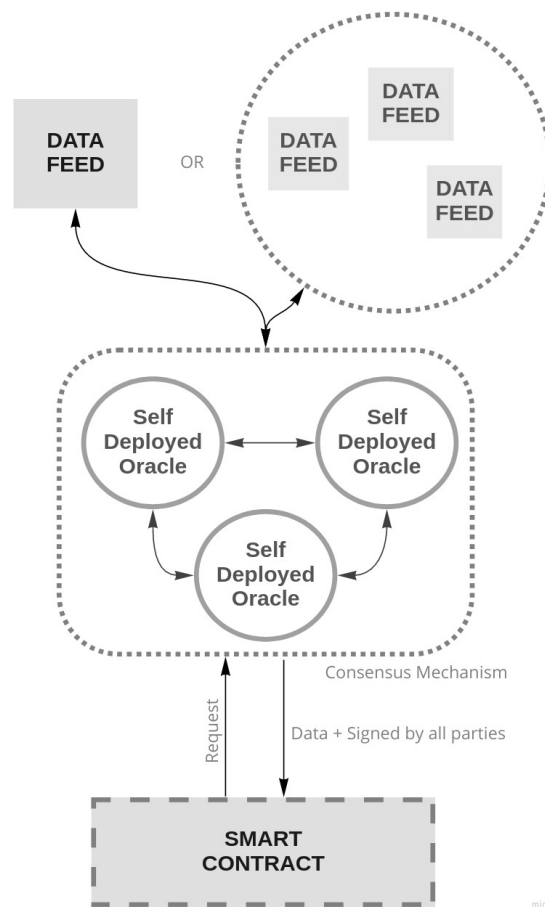


Figura 3.4: Multi-Party Self Hosted Oracle.

Capítulo 4

Implementation

On this section, I will discuss in detail the implementation of a trustable oracle, following the standard described in the previous chapter, on the Takai project.

4.1 Summary and conclusions

Implementation

Capítulo 5

Conclusions and Future Work

The oracle trust problem, is still rather recent, having emerged in 2015 with the deployment of smart contracts on the Ethereum blockchain. The systematic literature review, as far as it has been performed, and the non-academia research review reveal that most of the research and development is being done by the growing and excited blockchain community. Mostly by startups and single interested researchers.

Solving the trust problem and creating a standard for a secure middle-ware between blockchains and outside world information and application provides limitless range of future applications in terms of contracts. Creating, therefore, the grounds and the motivation for the work that will be developed on this thesis.

I hope that the work that will be developed in investigating the necessary requirements and research how oracle trust can be achieved allied with a proof-of-concept implementation on the Taikai projects will solidify the academia position on newly and ground breaking technologies such as the blockchain.

Conclusions and Future Work

Referências

- [ABV⁺18] John Adler, Ryan Berryhill, Andreas Veneris, Zissis Poulos, Neil Veira e Anastasia Kastania. *Astraea: A Decentralized Blockchain Oracle*. 8 2018. URL: <http://arxiv.org/abs/1808.00528>.
- [EH18] Jacob Eberhardt e Jonathan Heiss. Off-chaining Models and Approaches to Off-chain Computations. In *Proceedings of the 2nd Workshop on Scalable and Resilient Infrastructures for Distributed Ledgers - SERIAL'18*, pages 7–12, New York, New York, USA, 2018. ACM Press. URL: <http://dl.acm.org/citation.cfm?doid=3284764.3284766>, doi:10.1145/3284764.3284766.
- [EJN17] Steve Ellis, Ari Juels e Sergey Nazarov. *ChainLink A Decentralized Oracle Network*. Technical report, 2017. URL: <https://link.smartcontract.com/whitepaper>.
- [Gav14] Gavin Wood. *Ethereum: A secure decentralised generalised transaction ledger*. Technical report, Ethereum, 2014. URL: <http://gavwood.com/paper.pdf>.
- [Gor17] Gilroy Gordon. Provenance and authentication of oracle sensor data with block chain lightweight wireless network authentication scheme for constrained oracle sensors. 2017. URL: <http://library2.smu.ca/handle/01/27013>.
- [KKC07] B. Kitchenham, B. Kitchenham e S Charters. *Guidelines for performing Systematic Literature Reviews in Software Engineering*. 2007. URL: <http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.117.471>.
- [MM18] Francisco Javier Andrés Montoto Monroy. *Bitcoin gambling using distributed oracles in the blockchain*. 2018. URL: <http://repositorio.uchile.cl/handle/2250/151866>.
- [Nak09] Satoshi Nakamoto. *Bitcoin: A Peer-to-Peer Electronic Cash System*. Technical report, Bitcoin, 2009. URL: <https://bitcoin.org/bitcoin.pdf>.
- [Ora18] Oraclize.it. *Oraclize Documentation*, 2018. URL: <https://docs.oraclize.it/#security-deep-dive>.
- [ZCC⁺16] Fan Zhang, Ethan Cecchetti, Kyle Croman, Ari Juels e Elaine Shi. *Town Crier*. In *Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security - CCS'16*, pages 270–282, New York, New York, USA, 2016. ACM Press. URL: <http://dl.acm.org/citation.cfm?doid=2976749.2978326>, doi:10.1145/2976749.2978326.

REFERÊNCIAS

Anexo A