A Systematic Literature Review on Blockchain Oracles: State of Research, Challenges, and Trends

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Abstract

To enable data exchange between the Blockchain protocol (on-chain) and the real world (off-chain), e.g., non-Blockchain-based applications and systems, a software called Oracle is used [3]. Blockchain oracle is an important component in the use of off-chain data for on-chain smart contracts. However, there is limited scientific literature available on this important blockchain topic. Therefore, in this paper, a novel systematic literature review based on intelligent methods, e.g., information linking, topic clustering and focus identification through frequency calculations, is proposed. Thus, the current state of scientific research interest, content and challenges, and future research directions for blockchain oracles are identified. This paper shows that there is little unbiased literature that does not call oracles a problem. From the results of this new literature review framework, relevant areas of data handling and verification with blockchain oracles are identified for future research.

Keywords: Blockchain Oracle; Smart Contract; Bibliometric analysis; Intelligent methods.

1. Introduction

Distributed ledger technology, particularly blockchain technology, is ready to complete the status of technology testing and gradually be applied in real-world, economic business cases [48]. To exchange data between off-chain and on-chain, a type of translator between the different data protocols is needed. This connecting infrastructure is called “blockchain oracle” and regulates the exchange of data between off-chain applications and on-chain transactions for smart contracts [3]. Smart contracts are simple program code that can process transactions on blockchains automatically [72]. From a technical perspective, oracles are at an intermediate stage where they often lack the basic characteristics of a blockchain such as decentralization, tamper resistance, and transparency [1]. And so, a regular oracle passes incoming data from the non-blockchain environment to the chain without any prior verification of correctness, where smart contracts access the data directly without verifying. Thus, many oracles pose a security and trust problem. This issue is also known as the "oracle problem" [16].

The objective of this paper is to identify the current state of research, content and challenges, as well as future research directions for blockchain oracles using a systematic literature review. The structured literature search uses an iterative [83] and linking procedure for the search [89], and the results are completed with intelligent methods. As a result of the literature analysis, overlapping topics are identified and clustered accordingly [88], and the focus of each publication is determined for content classification [66]. The software Litmaps is used for the graphical representation and maps a network of all authors of the literature retrieved. The goal is to identify areas of blockchain oracle research that are poorly covered or unaddressed.

The paper is structured as followed: After the introduction in section 1, a literature review is conducted in section 2 to identify the main areas. Based on this, the results of the literature review are subjected to a bibliometric analysis in section 4. This is done using intelligent methods, namely information linking, topic clustering, and focus identification. Finally, section 5 provides a comprehensive discussion of the results and identifies potential research gaps.

2. Literature review approach

The systematic literature search (Fig. 1) is conducted according to vom Brocke et al. [83]. The relevant search strings are "*blockchain oracle*" and "*decentralized oracle*". Not mentioning blockchain would distort the search results. The search strings are searched in the title and abstract. Search delimitation is made by using the Boolean operators ‘AND’ and ‘OR’. For this purpose, five scientific databases, IEEEXplore, arXiv, MDPI, Science Direct and Springer Link, have been queried with the given search string. The syntax of the search term query varies depending on the requirements of each database (Tab. 1).

Database	Search String
IEEEXplore	("Document Title":blockchain oracle OR decentralized oracle AND "Abstract":blockchain oracle OR decentralized oracle)
arXiv	title="blockchain oracle"; OR title="decentralized oracle"; AND abstract="blockchain oracle"; OR abstract="decentralized oracle"
MDPI	advanced=(@(title)"decentralized oracle")|(@(title)"blockchain oracle"@(abstract)"decentralized oracle")|(@(abstract)"blockchain oracle")
Science Direct	title, abstract, keywords="blockchain oracle" OR "decentralized oracle"
Springer Link	title="blockchain+oracle"+or+"decentralized+oracle"

Tab. 1: Used databases and search strings.

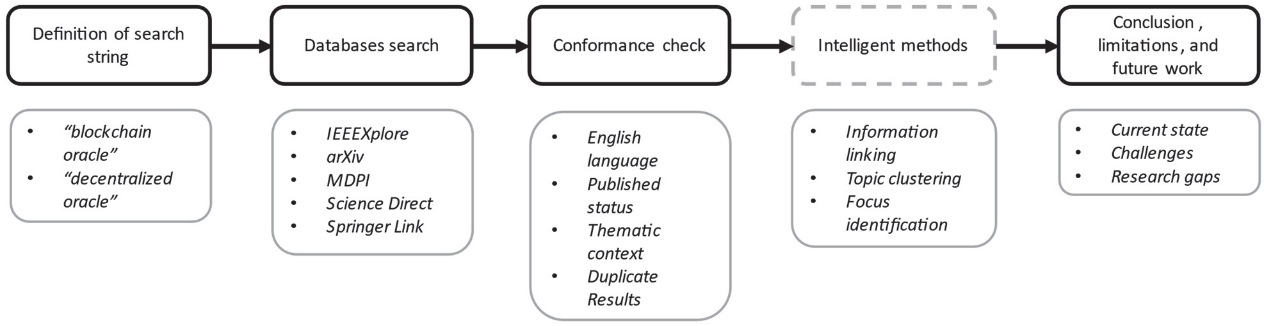

Fig. 1: Strategy of the systematic literature review.

The retrieved literature is checked for conformance, using only published English-language articles. Additionally, unfitting thematic results and duplicates are excluded. All remaining articles are analyzed via the following intelligent methods:

- **Information linking** is done by searching backward and forward through the relevant articles [89] to identify other relevant publications and establish a connection between the authors.
- **Topic clustering** examines content and topics for similarities and combines them through data abstraction. The results are presented in thematically hard clustered terms to identify and analyze important points in research [66]. The cluster terms result from thematic overlaps in the literature.
- **Focus identification** shows the frequency of content of the topics covered in the literature. This indicates statements about the importance of certain focal points as well as missing research.

After the literature analysis and consolidation, the results of the intelligent methods are evaluated. The results are processed in the conclusion, limitations, and future work sections. This is done by creating a research agenda that highlights the current state as well as future research. In an iterative process, the literature review cycle can then be repeated with more specific terms [83].

3. Literature review results

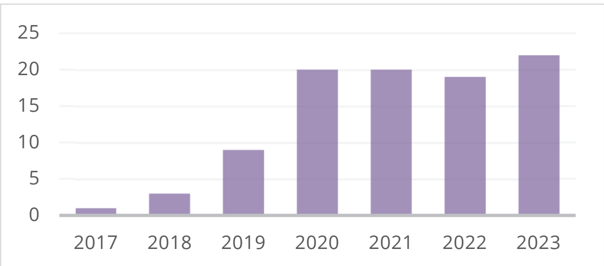

Fig. 2: Distribution of the published publications by year.

Following the strategy shown in Figure 1, a total of 85 scientific publications were found through the database search and after the conformance check. Nine more publications are added by the backward and forward search. A total of 94 published papers were found in the period from 2017 to 2023. Figure 2 shows the frequency distribution of the literature ordered by year of publication. While only one oracle-specific paper was published in 2017 [75], the number rises to a plateau of 20 publications in 2020 to 2023.

4. Intelligent methods analysis

The results of the systematic literature review are presented in this section with a bibliometric analysis using the intelligent methods: graphical information linking, overarching topic clustering and focus identification.

4.1. Information linking

The backward and forward search of information linkage has already been used for literature search. Some overlaps in subject areas and authors are found. Information linkage of the 94 publications found shows that four papers are cited particularly frequently (Table 2). Four papers have been identified as central through a considerably higher number of citations [1, 3, 10, 71]. It can be noted that 11 publications were cited on average between 8-14 times. 47 pieces of the found literature were not cross-cited [4-6, 8, 21, 23-25, 27, 30, 33-40, 42, 44, 46, 47, 51, 55-57, 59, 63, 64, 68, 70, 72, 73, 76, 79, 81, 82, 84, 87, 90, 92-96, 98, 99].

Title	Author/s	Number of Citations
Astraea: A Decentralized Blockchain Oracle	Adler et al. [1]	42
Trustworthy Blockchain Oracles: Review, Comparison, and Open Research Challenges	Al-Breiki et al. [3]	31
A Study of Blockchain Oracles	Abdeljalil Beniiche [10]	22
Augur: a decentralized oracle and prediction market platform	Peterson et al. [71]	22

Tab. 2: Highlighting the most frequently cited sources.

In order to show which authors are linked in terms of content, a graph is created that visualizes a bibliographic linkage of the literature retrieved. For a clearer representation of the connections between authors, only publications with at least eight cross-citations are shown graphically. Figure 3 shows the connections between 16 most cross-cited publications [1, 3. 10, 13, 16, 20, 41, 49, 53, 60, 61, 62, 71, 75, 77, 91]. The directed edges point in the direction of the made quote.

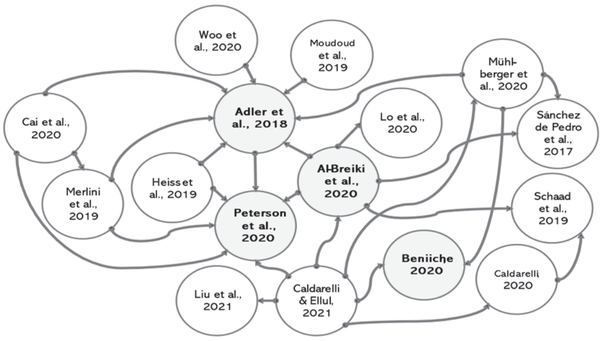

Fig. 3: Visualization of the 16 most cross-cited authors.

To draw a comprehensive picture of all links in the literature, Litmaps is used to populate the bibliography and create a map showing the referenced literature by author (Fig. 4). The dots represent the literature found and the lines show the "cited by" links. More frequently cited sources are presented in larger dots than publications with few or no citations. For better readability, not all points can be marked with the first author in each case. Three sources of the literature found [40, 57, 64] could not be mapped because they are not maintained by the software Litmaps.

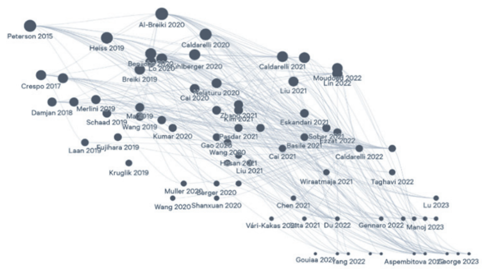

Fig. 4: Linking the authors with Litmaps.

Subsequently, a link between the papers is established based on the authors. The authors listed in Table 3 are assigned between two and a maximum of six published articles. The author Caldarelli has achieved the highest number of publications on blockchain oracle with six published articles [15-20].

Author	Count	Identified publications
Al-Breiki, H.	2	Al-Breiki et al., 2019 [2], Al-Breiki et al., 2020 [3]
Bartholic, M.	2	Bartholic et al., 2022 [7], Bartholic et al., 2023 [8]
Caldarelli, G.	6	Caldarelli et al., 2020 [15], Caldarelli 2020 [16], Caldarelli 2020 [17], Caldarelli & Ellul, 2021 [20], Caldarelli 2022 [18], Caldarelli 2023 [19]
Cai, Y.	2	Cai et al., 2020 [13], Cai et al., 2022 [14]
Liu, B.	2	Liu et al., 2021 [49], Liu et al., 2022 [50]
Pasdar, A.	2	Pasdar et al., 2021 [69], Pasdar et al., 2023 [70]
Wang, S.	2	Wang et al. 2019 [85], Wang & Yu 2020 [96]

Tab. 3: Overarching assignment of authors and publications.

4.2. Topic clustering

In this section, the literature is grouped according to the content of the title and abstract by topic. The scientific papers are analyzed, sorted thematically and grouped into suitable clusters for categorization. The thematic sorting identifies two clusters: *"design optimization"* and *"study"*. While literature classified as *"study"* analyzes the current state of research based on literature reviews, the literature classified as *"design optimization"* investigates approaches that deal with engineering procedures for the technical optimization of oracles. The design optimization is divided into further subcategories, namely data management, distributed systems, and verification (Fig. 5). We use a hard assignment to the clusters, so that the publications found can only be assigned to exactly one cluster. The four overarching clusters are:

- **Data management** is the management and transfer of data from off-chain to on-chain infrastructures via oracles.
- **Distributed systems** deal with the proper design of the decentralized multisystem infrastructure of oracles from an interoperability perspective.
- **Verification** is about checking the correctness of the off-chain data before transferring it to the blockchain protocol via oracle(s).
- **State of the art analysis** includes a literature review as a baseline effort and sometimes building on that to develop a method, framework, or prototype for using oracles in specific use cases.

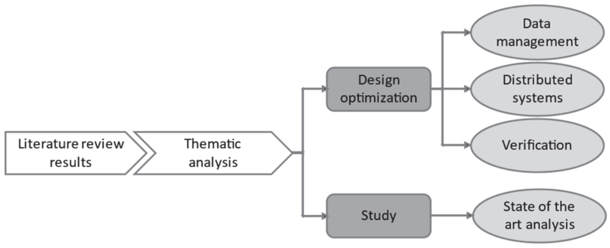

Fig. 5: Thematic categorization in the cluster approach.

The literature retrieved can be thematically categorized as the following (Tab. 4): Data management (17), Distributed systems (28), Verification (17), and in the literature review field, State of the art analysis (32).

Cluster	Publications
Data management	[24, 32, 33, 39, 46, 51, 59, 70, 72, 73, 78, 79, 86, 90, 93, 96, 97]
Distributed systems	[2, 11, 21, 22, 23, 27, 30, 31, 36, 37, 38, 42, 45, 55, 57, 58, 60, 61, 63, 64, 65, 71, 75, 80, 81, 91, 92, 95]
Verification	[1, 4, 13, 14, 26, 34, 50, 52, 56, 67, 68, 69, 76, 84, 85, 87, 98]
State of the art analysis	[3, 5, 6, 7, 8, 9, 10, 12, 15, 16, 17, 18, 19, 20, 25, 28, 29, 35, 40, 41, 43, 44, 47, 49, 53, 54, 62, 74, 77, 82, 94, 99]

Tab. 4: Cluster allocation of the found publications.

4.3. Focus identification

In this section, the topics of the publications are identified based on the focus areas and rated according to their frequency. The focus analysis was based on the title and abstract of the publications. A review of the software engineering literature without reference to an oracle use case is not the center of this section.

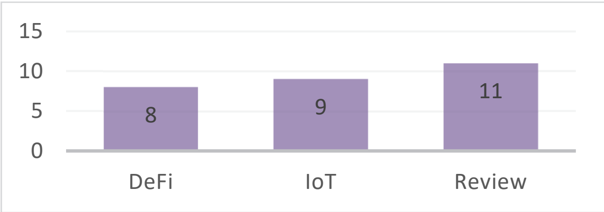

Fig. 6: Frequency distribution of the focus cluster.

The relevant use cases in the domains of Decentralized Finance (DeFi), Internet of Things (IoT), and Literature review are highlighted as focal points (Fig. 6). The term DeFi in connection with blockchain technology stands for the trustless and transparent provision of financial instruments without intermediaries [6]. The keyword IoT describes a network of interconnected electronic devices with limited capabilities [2]. The review relates to the conduct of a literature search. There are eight publications attributed to DeFi [6, 20, 24, 49, 50, 57, 87, 99] and seven to IoT [2, 23, 27, 59, 61,74, 82, 90, 91]. The literature review was recorded with 11 publications [3, 6, 16, 17, 18, 20, 23, 29, 35, 44, 74]. Some of the literature reviews also address the topics of DeFi [6, 20] or IoT [23, 74].

4.4. Evaluation of the results

This section summarizes the results of the intelligent methods. The number of found literature of 94 pieces in relation to the five queried scientific databases shows that there is relatively little literature about blockchain oracle. Since the beginning of this study, the number of publications has increased from one in 2017 to 23 per year in 2023 (Fig. 2). The results of the "Information linking" chapter show that the existing literature is often cross-cited, indicating that not much citable literature exists (Fig. 4). Half of the found publications were not cross-referenced and referred to more general blockchain sources. 43 of these papers were published in the last 2-3 years. This is indicative of the age of publication factor. Another observation is that articles in book publications are not cited from the Springer Link database. The number of most cited papers is very high in relation to the total number of publications (Tab. 2). The four most cited papers show strong interdependencies due to mutual cross-references. The lack of diversity in publications can also be confirmed by analyzing the authors. Seven authors (Tab. 3) were found to be exclusively responsible for 18 papers. One author, Caldarelli, stands out clearly with six publications. Caldarelli's works [15-20] are all classified under the category of literature review. Overall, the literature reviews settle on certain focus areas for oracles, which usually address only one problem, i.e., either the problem of centrality, security, or reliability. The topic clustering (Tab. 4) shows that research is conducted in about equal parts in the areas of Data management and verification. Distributed systems and the analysis of the state of the art receive more attention than the two previous topics. This is an indication that distributed oracle infrastructures have been already better researched than data management and verification structures in oracles. The identification of focus areas (Fig. 6) shows that some papers focused on specific use cases. This suggests that the most promising use cases for oracles are in a DeFi or IoT implementation or general literature reviews. The topic clustering from section 4.2 "state of the art analysis" contains the literature review results of the focus identification, but not vice versa. The cluster results contain many studies and comparisons on the technological implementation of blockchain oracles, but no literature review. However, this is only a small part of the total number of publications with a specific focus. Most publications cannot be assigned to any identifiable use case and deal with the technical implementation of oracles. It turns out that blockchain oracles are a topic in the areas mentioned, but the general technical benefits are explored more deeply than the application in concrete use cases.

5. Conclusion, limitations and future work

The goal of this paper is to provide an overview of the multi-layered research field of blockchain oracles. To this purpose, the systematic literature review is complemented by the application of intelligent methods. The analysis is carried out in three successive steps. First, the information of the authors of the literature is linked, then the topics are sorted according to content clusters and finally specific focus areas are identified. Overall, a multi-page analysis of the researched literature is performed, ranging from author categorization to topic categorization to focus analysis in real use cases. The literature results are thus placed in an overall context to each other. The small number of publications found, the many cross-references, the low diversification of the literature, and the few known authors indicate that there is still a need for research on blockchain oracles. Explicitly, the topics of data management and verification are less covered than literature reviews and distributed systems. This confirms initial research gaps in the general topic of blockchain oracles, especially in the area of verification and security in handling data.

Further studies can complement the literature search by querying higher-level AI-powered databases, such as Semantic Scholar, to identify content connections through the search and thus find further literature.

The literature search revealed that many publications on oracles are often concerned with the lack of typical blockchain properties. This disregards the fact that oracles are in a kind of in-between world. Blockchains can provide trust and transparency in data and transactions. These properties of a blockchain are not compromised by technical non-blockchain-based oracles. On the other hand, oracles should of course consistently meet these requirements in terms of data security and integrity. In the long run, research will evaluate and develop its own technical conception of oracles. In addition, this literature review has highlighted the need for standardized oracle development, as there are approaches to solutions from decentralized, consensus-based oracles. Another indication of future research direction is the development of best practices for oracles that can be used for universal use cases. Isolated use cases, such as DeFi or IoT, could be identified. This shows that much of the published literature is concerned with technical development and not with specific applications in particular business areas. This gap has to be addressed in future research.

Another oracle topic deals with the issue of verifying data before it is transferred to a blockchain. The reason for this is that, according to the credo of blockchains, the written transactions are trustworthy, secure and tamper-proof, while the data originating from third-party systems is not verified by oracles. This raises the important question of the particular unique selling proposition of blockchain and should be explored in further research.

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Literature references

[1] Adler, J., Berryhill, R., Veneris, A., Poulos, Z., Veira, N., Kastania, A. (2018): Augur: a Decentralized Oracle and Prediction Market Platform, in: Proceedings of the 2018 IEEE International Conference on Internet of Things (iThings) and IEEE Green Computing and Communications (GreenCom) and IEEE Cyber, Physical and Social Computing (CPSCom) and IEEE Smart Data (SmartData), page 1145–1152, doi:10.13140/2.1.1431.4563.

[2] Al Breiki, H., Al Qassem, L., Salah, K., Rehman, M. H. U., Sevtinovic, D. (2019): Decentralized Access Control for IoT Data Using Blockchain and Trusted Oracles, in: *2019 IEEE International Conference on Industrial Internet (ICII)*, Orlando, FL, USA, pp. 248-257, doi:10.1109/ICII.2019.00051.

[3] Al-Breiki, H., Rehman, M. H. U., Salah, K., Svetinovic, D. (2020): Trustworthy Blockchain Oracles: Review, Comparison, and Open Research Challenges, in: *IEEE Access*, vol. 8, pp. 85675-85685, doi:10.1109/ACCESS.2020.2992698.

[4] Almi'Ani, K., Lee, Y. C., Alrawashdeh T., Pasdar, A. (2023): Graph-Based Profiling of Blockchain Oracles, in: *IEEE Access*, vol. 11, pp. 24995-25007, doi:10.1109/ACCESS.2023.3254535.

[5] Antonio Pierro, G., and Mahugnon, H. (2023): An analysis of the Oracles used in Ethereum's blockchain, in: *2023 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER)*, Taipa, Macao, pp. 878-885, doi:10.1109/SANER56733.2023.00106.

[6] Aspembitova, A.T.; Bentley, M.A. (2023): Oracles in Decentralized Finance: Attack Costs, Profits and Mitigation Measures, in: *Entropy 2023*, 25(1), 60, doi:10.3390/e25010060

[7] Bartholic, M., Laszka, A., Yamamoto, G., Burger, E. W. (2022): A Taxonomy of Blockchain Oracles: The Truth Depends on the Question, in: *2022 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, Shanghai, China, pp. 1-15, doi:10.1109/ICBC54727.2022.9805555.

[8] Bartholic, M., Burger, E. W., Matsuo, S., Jung, T. (2023): Reputation as Contextual Knowledge: Incentives and External Value in Truthful Blockchain Oracles, in: *2023 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, Dubai, United Arab Emirates, pp. 1-9, doi:10.1109/ICBC56567.2023.10174903.

[9] Basile, D., Goretti, V., Di Ciccio, C., Kirrane, S. (2021): Enhancing Blockchain-Based Processes with Decentralized Oracles, in: González Enríquez, J., Debois, S., Fettke, P., Plebani, P., van de Weerd, I., Weber, I. (eds) Business Process Management: Blockchain and Robotic Process Automation Forum, BPM 2021, Lecture Notes in Business Information Processing, vol 428. Springer, Cham. doi:10.1007/978-3-030-85867-4_8.

[10] Beniiche, A. (2020): A Study of Blockchain Oracles, in: arXiv: 2004.07140.

[11] Berger, B., Huber, S., Pfeifhofer, S. (2020): OraclesLink: An architecture for secure oracle usage, in: *2020 Second International Conference on Blockchain Computing and Applications (BCCA)*, Antalya, Turkey, pp. 66-72, doi:10.1109/BCCA50787.2020.9274455.

[12] Boi, M., Pinna, A., Lunesu, M. I. (2023): Blockchain oracles for document certification: A case study., in: *2023 IEEE International Conference on Software Analysis, Evolution and Reengineering (SANER)*, Taipa, Macao, pp. 855-864, doi:10.1109/SANER56733.2023.00103.

[13] Cai, Y., Fragkos, G., Tsiropoulou, E. E., Veneris, A. (2020): A Truth-Inducing Sybil Resistant Decentralized Blockchain Oracle, in: *2020 2nd Conference on Blockchain Research & Applications for Innovative Networks and Services (BRAINS)*, Paris, France, pp. 128-135, doi:10.1109/BRAINS49436.2020.9223272.

[14] Cai, Y., Irtija, N., Tsiropoulou, E. E., Veneris, A. (2022): Truthful Decentralized Blockchain Oracles, in: *International Journal of Network Management*; 32(2):e2179, doi:10.1002/nem.2179.

[15] Caldarelli, G., Rossignoli, C., Zardini, A. (2020): Overcoming the Blockchain Oracle Problem in the Traceability of Non-Fungible

Products, in: *Sustainability*, 12(6):2391, doi:10.3390/su12062391.
[16] Caldarelli, G. (2020): Understanding the Blockchain Oracle Problem: A Call for Action., in: *Information,* 11(11):509, doi:10.3390/info11110509.
[17] Caldarelli, G. (2020): Real-world blockchain applications under the lens of the oracle problem. A systematic literature review, in: *2020 IEEE International Conference on Technology Management, Operations and Decisions (ICTMOD)*, Marrakech, Morocco, pp. 1-6, doi:10.1109/ICTMOD49425.2020.9380598.
[18] Caldarelli, G. (2022): Overview of Blockchain Oracle Research, in: *Future Internet*; 14(6):175, doi:10.3390/fi14060175.
[19] Caldarelli, G. (2023): Before Ethereum. The Origin and Evolution of Blockchain Oracles, in: *IEEE Access*, vol. 11, pp. 50899-50917, doi:10.1109/ACCESS.2023.3279106.
[20] Caldarelli, G., Ellul, J. (2021): The Blockchain Oracle Problem in Decentralized Finance—A Multivocal Approach, in: *Applied Sciences,* 11(16):7572, doi:10.3390/app11167572.
[21] Chen, S., Zhu, J., Lin, Z., Huang, J., Tang, Y. (2021): How to Make Smart Contract Smarter, in: Sun, Y., Liu, D., Liao, H., Fan, H., Gao, L. (eds) Computer Supported Cooperative Work and Social Computing, ChineseCSCW 2020, Communications in Computer and Information Science, vol 1330, Springer, Singapore, doi:10.1007/978-981-16-2540-4_54.
[22] Chen, L., Yuan, R., Xia, Y. (2021): Tora: A Trusted Blockchain Oracle Based on a Decentralized TEE Network, in: *2021 IEEE International Conference on Joint Cloud Computing (JCC)*, Oxford, United Kingdom, pp. 28-33, doi:10.1109/JCC53141.2021.00016.
[23] Chung, K. H. Y., Li, D., Adriaens, P. (2023): Technology-enabled financing of sustainable infrastructure: A case for blockchains and decentralized oracle networks, in: *Technological Forecasting and Social Change*, Volume 187, 122258, ISSN 0040-1625, doi:10.1016/j.techfore.2022.122258.
[24] Cioara, T., Pop, C., Zanc, R., Anghel, I., Antal, M., Salomie, I. (2020): Smart Grid Management Using Blockchain: Future Scenarios and Challenges, in: *2020 19th RoEduNet Conference: Networking in Education and Research (RoEduNet)*, Bucharest, Romania, pp. 1-5, doi:10.1109/RoEduNet51892.2020.9324874.
[25] Damjan, M. (2018): The interface between blockchain and the real world, in: Ragion Pratica, pp. 379-406, doi:10.1415/91545.
[26] Di Gennaro, M., Italiano, L., Meroni, G., Quattrocchi, G. (2022): *DeepThought*: A Reputation and Voting-Based Blockchain Oracle, in: Troya, J., Medjahed, B., Piattini, M., Yao, L., Fernández, P., Ruiz-Cortés, A. (eds) Service-Oriented Computing, ICSOC 2022, Lecture Notes in Computer Science, vol 13740, Springer, Cham, doi:10.1007/978-3-031-20984-0_26.
[27] Du, Y., Li, J., Shi, L., Wang, Z., Wang, T., Han, Z. (2022): A Novel Oracle-aided Industrial IoT Blockchain: Architecture, Challenges, and Potential Solutions, in: *IEEE Network*, doi:10.1109/MNET.103.2100395.
[28] Eskandari, S., Salehi, M., Gu, W. G., Clark, J. (2021): SoK: oracles from the ground truth to market manipulation, in: *Proceedings of the 3rd ACM Conference on Advances in Financial Technologies (AFT '21), Association for Computing Machinery,* New York, NY, USA, pp. 127–141, doi:10.1145/3479722.3480994.
[29] Ezzat, S. K., Saleh, Y. N. M., Abdel-Hamid, A. A. (2022): Blockchain Oracles: State-of-the-Art and Research Directions, in: *IEEE Access*, vol. 10, pp. 67551-67572, doi:10.1109/ACCESS.2022.3184726.
[30] Fuertes Blanco, A., Shi, Z., Roy, D., Zhao, Z. (2023): Improving the Resiliency of Decentralized Crowdsourced Blockchain Oracles, in: Mikyška, J., de Mulatier, C., Paszynski, M., Krzhizhanovskaya, V. V., Dongarra, J. J., Sloot, P.M. (eds) Computational Science – ICCS 2023. ICCS 2023, Lecture Notes in Computer Science, vol 14073, Springer, Cham, doi:10.1007/978-3-031-35995-8_1.
[31] Fujihara, A. (2020): Proposing a Blockchain-Based Open Data Platform and Its Decentralized Oracle, in: Barolli, L., Nishino, H., Miwa, H. (eds) Advances in Intelligent Networking and Collaborative Systems, INCoS 2019, Advances in Intelligent Systems and Computing, vol 1035, Springer, Cham, doi:10.1007/978-3-030-29035-1_19.
[32] Gao, Z., Li, H., Xiao, K., Wang, Q. (2020): Cross-chain Oracle Based Data Migration Mechanism in Heterogeneous Blockchains, in: *2020 IEEE 40th International Conference on Distributed Computing Systems (ICDCS)*, Singapore, Singapore, pp. 1263-1268, doi:10.1109/ICDCS47774.2020.00162.
[33] Gao, Z., Zhuang, Z., Lin, Y., Rui, L., Yang, Y., Zhao, C., Mo, Z. (2021): Select-Storage: A New Oracle Design Pattern on Blockchain, in: *2021 IEEE 20th International Conference on Trust, Security and Privacy in Computing and Communications (TrustCom)*, Shenyang, China, pp. 1177-1184, doi:10.1109/TrustCom53373.2021.00159.
[34] George, W. (2023): Strategic behaviour and manipulation resistance in Peer-to-Peer, crowdsourced information gathering, in: *Mathematical Social Sciences*, Volume 124, pp. 1-23, ISSN 0165-4896, doi:10.1016/j.mathsocsci.2023.04.002.
[35] Gonçalves, M. J. A., Pereira, R. H., Coelho, M. A. G. M. (2022): User Reputation on E-Commerce: Blockchain-Based Approaches, in: *Journal of Cybersecurity and Privacy,* 2(4):907-923, doi:10.3390/jcp2040046.
[36] Goswami, S., Danish, S. M., Zhang, K. (2022): Towards a middleware design for efficient blockchain oracles selection, in: *2022 Fourth International Conference on Blockchain Computing and Applications (BCCA)*, San Antonio, TX, USA, pp. 55-62, doi:10.1109/BCCA55292.2022.9922433.
[37] Gouiaa, R., Hdhili, F., Jansen, M. (2022): A Dag Based Decentralized Oracle Model: Implementation and Evaluation, in: Prieto, J., Partida, A., Leitão, P., Pinto, A. (eds) Blockchain and Applications, BLOCKCHAIN 2021, Lecture Notes in Networks and Systems, vol 320, Springer, Cham, doi:10.1007/978-3-030-86162-9_31.
[38] Gupta, A., Gupta, R., Jadav, D., Tanwar, S., Kumar, N., Shabaz, M. (2023): Proxy smart contracts for zero trust architecture implementation in Decentralised Oracle Networks based applications, in: *Computer Communications*, Volume 206, pp. 10-21, ISSN 0140-3664, doi:10.1016/j.comcom.2023.04.022.
[39] Hasan, M., Ogan, K., Starly, B. (2021): Hybrid Blockchain Architecture for Cloud Manufacturing-as-a-service (CMaaS) Platforms with Improved Data Storage and Transaction Efficiency, in: *Procedia Manufacturing*, Volume 53, pp. 594-605, ISSN 2351-9789, doi:10.1016/j.promfg.2021.06.060.
[40] Hassan, A., Makhdoom, I., Iqbal, W., Ahmad, A., Raza, A. (2023): From trust to truth: Advancements in mitigating the Blockchain Oracle problem, in: Journal of Network and Computer Applications, Volume 217, 103672, ISSN 1084-8045, doi:10.1016/j.jnca.2023.103672.

[41] Heiss, J., Eberhardt, J., Tai, S. (2019): From Oracles to Trustworthy Data On-Chaining Systems, in: *2019 IEEE International Conference on Blockchain (Blockchain)*, Atlanta, GA, USA, pp. 496-503, doi:10.1109/Blockchain.2019.00075.

[42] Huang, M., Cao, S., Li, X., Huang, K., Zhang, X. (2022): Defending Data Poisoning Attack via Trusted Platform Module and Blockchain Oracle, in: *ICC 2022 - IEEE International Conference on Communications*, Seoul, Korea, Republic of, pp. 1245-1250, doi:10.1109/ICC45855.2022.9838252.

[43] Kaleem, M., Shi, W. (2021): Demystifying Pythia: A Survey of ChainLink Oracles Usage on Ethereum, in: Bernhard, M., *et al.* Financial Cryptography and Data Security, FC 2021 International Workshops, FC 2021, Lecture Notes in Computer Science(), vol 12676, Springer, Berlin, Heidelberg, doi:10.1007/978-3-662-63958-0_10.

[44] Kruglik, S., Nazirkhanova, K., Yanovich, Y. (2019): Challenges beyond blockchain: scaling, oracles and privacy preserving, in: *2019 XVI International Symposium "Problems of Redundancy in Information and Control Systems" (REDUNDANCY)*, Moscow, Russia, pp. 155-158, doi:10.1109/REDUNDANCY48165.2019.9003331.

[45] Kumar, M., Nikhil, N., Singh, R. (2020): Decentralising Finance using Decentralised Blockchain Oracles, in: *2020 International Conference for Emerging Technology (INCET)*, Belgaum, India, pp. 1-4, doi:10.1109/INCET49848.2020.9154123.

[46] Lin, I.-C., Kuo, C.-W. (2023): Trustworthy Blockchain Oracles for Smart Contracts, in: Tsihrintzis, G.A., Wang, SJ., Lin, IC. (eds) 2021 International Conference on Security and Information Technologies with AI, Internet Computing and Big-data Applications, Smart Innovation, Systems and Technologies, vol 314, Springer, Cham, doi:10.1007/978-3-031-05491-4_38.

[47] Lin, S.-Y., Zhang, L., Li, J., Sun, Y. (2022): A survey of application research based on blockchain smart contract, in: *Wireless Netw 28*, pp. 635–690, doi:10.1007/s11276-021-02874-x.

[48] Litan, A. (2022): Gartner Hype Cycle for Blockchain and Web3, 2022, https://blogs.gartner.com/avivah-litan/2022/07/22/gartner-hype-cycle-for-blockchain-and-web3-2022/, 29/07/2023.

[49] Liu, B., Szalachowski, P., Zhou, J. (2021): A First Look into DeFi Oracles," *2021 IEEE International Conference on Decentralized Applications and Infrastructures (DAPPS)*, United Kingdom, pp. 39-48, doi:10.1109/DAPPS52256.2021.00010.

[50] Liu, B., Zhou, J., Lim, Y. Z. (2022): Being Accountable Never Cheats: An Incentive Protocol for DeFi Oracles, in: *2022 IEEE International Conference on Decentralized Applications and Infrastructures (DAPPS)*, Newark, CA, USA, pp. 1-10, doi:10.1109/DAPPS55202.2022.00009.

[51] Liu, X., Chen, R., Chen, Y.-W., Yuan, S.-M. (2018): Off-chain Data Fetching Architecture for Ethereum Smart Contract, in: *2018 International Conference on Cloud Computing, Big Data and Blockchain (ICCBB)*, Fuzhou, China, pp. 1-4, doi:10.1109/ICCBB.2018.8756348.

[52] Liu, X., Feng, J. (2021): Trusted Blockchain Oracle Scheme Based on Aggregate Signature, in: *Journal of Computer and Communications*, 09. 95-109, doi:10.4236/jcc.2021.93007.

[53] Lo, S. K., Xu, X., Staples, M., Yao, L. (2020): Reliability analysis for blockchain oracles, in: *Computers & Electrical Engineering*, Volume 83, 106582, ISSN 0045-7906, doi:10.1016/j.compeleceng.2020.106582.

[54] Lu, W., Li, X., Xue, F., Zhao, R., Wu, L., Yeh, A. G. O. (2021): Exploring smart construction objects as blockchain oracles in construction supply chain management, in: *Automation in Construction*, Volume 129, 103816, ISSN 0926-5805, doi:10.1016/j.autcon.2021.103816.

[55] Lu, S., Pei, J., Zhao, R., Yu, X., Zhang, X., Li, J., Yang, G. (2023): CCIO: A Cross-Chain Interoperability Approach for Consortium Blockchains Based on Oracle, in: *Sensors,* 23(4):1864, doi:10.3390/s23041864.

[56] Lv, P., Zhang, X., Liu, J., Wei, T., Xu, J. (2021): Blockchain Oracle-Based Privacy Preservation and Reliable Identification for Vehicles, in: Liu, Z., Wu, F., Das, S.K. (eds) Wireless Algorithms, Systems, and Applications, WASA 2021, Lecture Notes in Computer Science(), vol 12939, Springer, Cham, doi:10.1007/978-3-030-86137-7_54.

[57] Lys, L., Potop-Butucaru, M. (2022): Distributed Blockchain Price Oracle, in: Koulali, MA., Mezini, M. (eds) Networked Systems, NETYS 2022, Lecture Notes in Computer Science, vol 13464, Springer, Cham, doi:10.1007/978-3-031-17436-0_4.

[58] Ma, L., Kaneko, K., Sharma, S., Sakurai, K. (2019): Reliable Decentralized Oracle with Mechanisms for Verification and Disputation, in: *2019 Seventh International Symposium on Computing and Networking Workshops (CANDARW)*, Nagasaki, Japan, pp. 346-352, doi:10.1109/CANDARW.2019.00067.

[59] Manoj T., Makkithaya, K., Narendra, V. G. (2023): A trusted IoT data sharing and secure oracle based access for agricultural production risk management, in: *Computers and Electronics in Agriculture*, Volume 204, 107544, ISSN 0168-1699, doi:10.1016/j.compag.2022.107544.

[60] Merlini, M., Veira, N., Berryhill, R., Veneris, A. (2019): On Public Decentralized Ledger Oracles via a Paired-Question Protocol, in: *2019 IEEE International Conference on Blockchain and Cryptocurrency (ICBC)*, Seoul, Korea (South), pp. 337-344, doi:10.1109/BLOC.2019.8751484.

[61] Moudoud, H., Cherkaoui, S., Khoukhi, L. (2019): An IoT Blockchain Architecture Using Oracles and Smart Contracts: the Use-Case of a Food Supply Chain, in: *2019 IEEE 30th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Istanbul, Turkey, pp. 1-6, doi:10.1109/PIMRC.2019.8904404.

[62] Mühlberger, R., Bachhofner, S., Castelló Ferrer, E., Di Ciccio, C., Weber, I., Wöhrer, M., Zdun, U. (2020): Foundational Oracle Patterns: Connecting Blockchain to the Off-Chain World, in: *Lecture Notes in Business Information Processing*, Springer International Publishing, pp. 35-51, doi:10.1007/978-3-030-58779-6_3.

[63] Müller, M., Rodriguez Garzon, S., Küpper, A. (2020): COST: A Consensus-Based Oracle Protocol for the Secure Trade of Digital Goods, in: *2020 IEEE International Conference on Decentralized Applications and Infrastructures (DAPPS)*, Oxford, UK, pp. 72-81, doi:10.1109/DAPPS49028.2020.00008.

[64] Naderi, H., Shojaei, A., Ly, R. (2023): Autonomous construction safety incentive mechanism using blockchain-enabled tokens and vision-based techniques, in: *Automation in Construction*, Volume 153, 104959, ISSN 0926-5805, doi:10.1016/j.autcon.2023.104959.

[65] Nelaturu, K., Adler, J., Merlini, M., Berryhill, R., Veira, N., Poulos, Z., Veneris, A. (2020): On Public Crowdsource-Based Mechanisms for a Decentralized Blockchain Oracle, in: *IEEE Transactions on Engineering Management*, vol. 67, no. 4, pp. 1444-1458, doi:10.1109/TEM.2020.2993673.

[66] Nitsche, A.-M., Schumann, C.-A., Franczyk, B., Reuther, K. (2021): Mapping supply chain collaboration research: a machine learning-based literature review, in: *International Journal of Logistics Research and Applications*, doi:10.1080/13675567.2021.2001446.

[67] Park, J., Kim, H., Kim, G., Ryou, J. (2021): Smart Contract Data Feed Framework for Privacy-Preserving Oracle System on Blockchain, in: *Computers*, 10(1):7, doi:10.3390/computers10010007.

[68] Park, S., Bastani, O., Kim, T. (2023): ACon²: Adaptive Conformal Consensus for Provable Blockchain Oracles, doi:10.48550/arXiv.2211.09330.

[69] Pasdar, A., Dong, Z., Choon Lee, Y. (2021): Blockchain Oracle Design Patterns, doi:10.48550/arXiv.2106.09349.

[70] Pasdar, A., Lee, Y. C., Ryan, P., Dong, Z. (2023): A Blockchain Oracle-Based API Service for Verifying Livestock DNA Fingerprinting, in: Troya, J., *et al.* Service-Oriented Computing – ICSOC 2022 Workshops, ICSOC 2022, Lecture Notes in Computer Science, vol 13821, Springer, Cham, doi:10.1007/978-3-031-26507-5_7.

[71] Peterson, J., Krug, J., Zoltu, M., Williams, A. K., Alexander, S. (2020): Augur: a Decentralized Oracle and Prediction Market Platform, doi: 10.13140/2.1.1431.4563.

[72] Popchev, I., Radeva, I., Doukovska, L. (2023): Oracles Integration in Blockchain-Based Platform for Smart Crop Production Data Exchange, in: *Electronics*; 12(10):2244, doi:10.3390/electronics12102244.

[73] Pupyshev, A., Dzhafarov, E., Sapranidi, I., Kardanov, I., Khalilov, S., Laureyssens, S. (2020): SuSy: a blockchain-agnostic cross-chain asset transfer gateway protocol based on Gravity, doi:10.48550/arXiv.2008.13515.

[74] Sadawi, A. A., Hassan, M. S., Ndiaye, M. (2022): On the Integration of Blockchain With IoT and the Role of Oracle in the Combined System: The Full Picture, in: *IEEE Access*, vol. 10, pp. 92532-92558, doi:10.1109/ACCESS.2022.3199007.

[75] Sánchez De Pedro, A., Levi, D., Cuende, L. I. (2017): Witnet: A Decentralized Oracle Network Protocol, doi: 10.13140/RG.2.2.28152.34560.

[76] Sata, B., Berlanga, A., Chanel, C. P. C., Lacan, J. (2021): Connecting AI-based Oracles to Blockchains via an Auditable Auction Protocol, in: *2021 3rd Conference on Blockchain Research & Applications for Innovative Networks and Services (BRAINS)*, Paris, France, pp. 23-24, doi:10.1109/BRAINS52497.2021.9569808.

[77] Schaad, A., Reski, T., Winzenried, O. (2019): Integration of a Secure Physical Element as a Trusted Oracle in a Hyperledger Blockchain, in: *International Conference on E-Business and Telecommunication Networks*, doi:10.5220/0007957104980503.

[78] Sober, M., Scaffino, G., Spanring, C., Schulte, S. (2021): A Voting-Based Blockchain Interoperability Oracle, in: *IEEE International Conference on Blockchain (Blockchain)*, Melbourne, Australia, pp. 160-169, doi:10.1109/Blockchain53845.2021.00030.

[79] Stefanescu, D., Galán-García, P., Montalvillo, L., Unzilla, J., Urbieta, A. (2023): Industrial Data Homogenization and Monitoring Scheme with Blockchain Oracles, in: *Smart Cities*; 6(1):263-290, doi:10.3390/smartcities6010013.

[80] Taghavi, M., Bentahar, J., Otrok, H., Bakhtiyari, K. (2023): A reinforcement learning model for the reliability of blockchain oracles, in: *Expert Systems with Applications*, Volume 214, 119160, ISSN 0957-4174, doi:10.1016/j.eswa.2022.119160.

[81] van der Laan, B., Ersoy, O., Erkin, Z. (2019): MUSCLE: authenticated external data retrieval from multiple sources for smart contracts, in: *Proceedings of the 34th ACM/SIGAPP Symposium on Applied Computing (SAC '19)*, Association for Computing Machinery, New York, NY, USA, pp. 382–391, doi:10.1145/3297280.3297320.

[82] Vári-Kakas, S., Poszet, O., Mirela Pater, A., Valentina Moisi, E., Vári-Kakas, A. (2021): Issues Related to the Use of Blockchains in IoT Applications, in: *2021 16th International Conference on Engineering of Modern Electric Systems (EMES)*, Oradea, Romania, pp. 1-4, doi:10.1109/EMES52337.2021.9484103.

[83] vom Brocke, J., Simons, A., Niehaves, B., Reimer, K., Plattfaut, R., Cleven, A. (2009): Reconstructing the Giant: On the Importance of Rigour in Documenting the Literature Search Process, in: *European Conference on Information Systems.*

[84] Wang, S., Yu, X. (2020): Research on Trusted Identification of Blockchain Uploaded Data, in: *2020 IEEE International Conference on Artificial Intelligence and Computer Applications (ICAICA)*, Dalian, China, pp. 1036-1044, doi:10.1109/ICAICA50127.2020.9181948.

[85] Wang, S., Lu, H., Sun, X., Yuan, Y., Wang, F.-Y. (2019): A Novel Blockchain Oracle Implementation Scheme Based on Application Specific Knowledge Engines, in: *2019 IEEE International Conference on Service Operations and Logistics, and Informatics (SOLI)*, Zhengzhou, China, pp. 258-262, doi:10.1109/SOLI48380.2019.8955107.

[86] Wang, Y., Liu, H., Wang, J., Wang, S. (2020): Efficient Data Interaction of Blockchain Smart Contract with Oracle Mechanism, in: *2020 IEEE 9th Joint International Information Technology and Artificial Intelligence Conference (ITAIC)*, Chongqing, China, pp. 1000-1003, doi:10.1109/ITAIC49862.2020.9338784.

[87] Wang, Y., Li, J., Su, Z., Wang, Y. (2022): Arbitrage Attack: Miners of the World, Unite!, in: Eyal, I., Garay, J. (eds) Financial Cryptography and Data Security, FC 2022, Lecture Notes in Computer Science, vol 13411, Springer, Cham, doi:10.1007/978-3-031-18283-9_23.

[88] Watson, R. T., Webster, J. (2020): Analyzing the past to prepare for the future: Writing a literature review a roadmap for release 2.0, in: *Journal of Decision Systems*, 29:3, pp. 129-147, doi:10.1080/12460125.2020.1798591.

[89] Webster, J., Watson, R. T. (2002): Analyzing the Past to Prepare for the Future: Writing a Literature Review, in: *MIS Quarterly 26*, no. 2: xiii–xxiii, doi:10.2307/4132319.

[90] Wiraatmaja, C., Zhang, Y., Sasabe, M., Kasahara, S. (2021): Cost-Efficient Blockchain-Based Access Control for the Internet of Things, in: *2021 IEEE Global Communications Conference (GLOBECOM)*, Madrid, Spain, pp. 1-6, doi:10.1109/GLOBECOM46510.2021.9685205.

[91] Woo, S., Song, J., Park, S. (2020): A Distributed Oracle Using Intel SGX for Blockchain-Based IoT Applications, in: *Sensors*; 20(9):2725, doi:10.3390/s20092725.

[92] Wu, X., Wang, H., Ge, C., Zhou, L., Huang, Q., Kong, L., Cui, L., Liu, Z. (2022): *CCOM*: Cost-Efficient and Collusion-Resistant Oracle Mechanism for Smart Contracts, in: Nguyen, K., Yang, G., Guo, F., Susilo, W. (eds) Information Security and Privacy, ACISP 2022, Lecture Notes in Computer Science, vol 13494, Springer, Cham, doi:10.1007/978-3-031-22301-3_22.

[93] Yadav, S., Rastogi, S., Soni, S., Kshitij, P., Malsa, N., Gupta, V., Ghosh, A., Shaw, R. N. (2023): Distributed Hotel Chain Using Blockchain and Chainlink, in: Shaw, R.N., Paprzycki, M., Ghosh, A. (eds) Advanced Communication and Intelligent Systems,

ICACIS 2022, Communications in Computer and Information Science, vol 1749, Springer, Cham, doi:10.1007/978-3-031-25088-0_43.
[94] Yang, F., Lei, L., Chen, L. (2022): Method of Interaction between Blockchain and the World outside the Chain based on Oracle Machine, in: *2022 IEEE 8th Intl Conference on Big Data Security on Cloud (BigDataSecurity), IEEE Intl Conference on High Performance and Smart Computing, (HPSC) and IEEE Intl Conference on Intelligent Data and Security (IDS)*, Jinan, China, pp. 101-106, doi:10.1109/BigDataSecurityHPSCIDS54978.2022.00028.
[95] Yang, T., Sun, Q., Chen, F. (2022): TransOra: A Transaction-preserving and Transparent Distributed Oracle on Permissioned Blockchain For Hybrid Smart Contracts, in: *2022 3rd International Conference on Computing, Networks and Internet of Things (CNIOT)*, Qingdao, China, pp. 1-11, doi:10.1109/CNIOT55862.2022.00010.
[96] Yu, H., Wang, H. (2023): Lattice-Based Threshold Signcryption for Blockchain Oracle Data Transmission, in: *IEEE Transactions on Intelligent Transportation Systems*, doi:10.1109/TITS.2023.3276920.
[97] Zhang, C., Zhu, L., Xu, C., Sharif, K. (2021): PRVB: Achieving Privacy-Preserving and Reliable Vehicular Crowdsensing via Blockchain Oracle, in: *IEEE Transactions on Vehicular Technology*, vol. 70, no. 1, pp. 831-843, doi:10.1109/TVT.2020.3046027.
[98] Zhang, S., Zhang, Y., Jing, X., Diao, X., Huang, G. (2022): DataAttest: A Framework to Attest Off-Chain Data Authenticity, in: Svetinovic, D., Zhang, Y., Luo, X., Huang, X., Chen, X. (eds) Blockchain and Trustworthy Systems, BlockSys 2022, Communications in Computer and Information Science, vol 1679, Springer, Singapore, doi:10.1007/978-981-19-8043-5_5.
[99] Zhao, Y., Kang, X., Li, T., Chu, C.-K., Wang, H. (2022): Towards Trustworthy DeFi Oracles: Past, Present and Future, IEEE Access, doi:10. 1-1. 10.1109/ACCESS.2022.3179374.