THESIS RESUME

METHODS AND TECHNIQUES FOR ENSURING THE INTEROPERABILITY OF ARTIFICIAL INTELLIGENCE ALGORITHMS IN DECENTRALIZED BLOCKCHAIN NETWORKS

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Introduction

The integration of Artificial Intelligence (AI) algorithms within decentralized blockchain networks presents significant challenges related to communication and interoperability. Existing approaches often lack the frameworks needed for seamless interaction between AI agents across distributed environments. This thesis addresses these challenges by proposing innovative methods and techniques to enhance the interoperability of AI algorithms within decentralized blockchain ecosystems. The research explores the intersection of AI and Distributed Ledger Technology (DLT), presenting a structured approach to developing decentralized communication protocols that enable AI agents to function efficiently and collaboratively across multiple blockchain layers.

Central to this research is the development of an ontology-based system designed to improve communication and interoperability among AI agents within decentralized networks. A multi-layered ontology model is introduced, facilitating seamless interaction and data exchange among heterogeneous AI entities.

The thesis begins by providing an overview of identity management models—self-sovereign, decentralized, and centralized—and their security implications, including key management, encryption techniques, and secure computation methods. It evaluates Oracle protocols such as TLSnotary, DECO, and Chainlink, which are critical for interfacing blockchains with external data. The study also examines virtualized execution environments like KATA Containers, SCONE, and Trusted Execution Environments, assessing their role in enabling scalable and secure AI applications. Additionally, it explores decentralized storage solutions, including Swarm, IPFS, and BigchainDB, and their impact on data integrity and accessibility. The role of ontology-based data exchange is highlighted, emphasizing its importance in achieving semantic compatibility among AI agents and supporting the evolution of blockchain architectures for enterprise applications.

The thesis proposes a decentralized ontology versioning model to support multi-organizational data exchange. Detailed descriptions of the model's architecture, data management protocols, voting system, and consensus mechanism provide a robust framework for integrating AI with distributed ledger technologies. This model enhances data representation, standardizes communication between diverse AI systems, and addresses key challenges such as algorithmic compatibility, data consistency, and secure operation of AI-driven tasks across decentralized nodes.

The performance of the proposed model is evaluated through benchmarks and optimizations, demonstrating its effectiveness in improving AI agent interoperability. Comparative analysis highlights the model's superiority across various metrics, including data format compatibility, environmental adaptability, and agent interaction efficiency. The model not only enhances the functionality of AI algorithms within blockchain ecosystems but also offers a scalable framework adaptable to diverse application domains, bridging the gap between AI and blockchain technologies and paving the way for more interoperable, advanced, and secure decentralized applications.

Through empirical validation and theoretical analysis, the thesis establishes the efficacy of the proposed ontology-based approach in fostering cohesive and efficient communication among AI agents. The findings underscore the potential of ontology systems to advance decentralized AI networks, promoting more adaptive and collaborative AI systems across various fields. The ontology framework enables AI agents to navigate and utilize decentralized environments effectively.

Addressing the critical challenge of integrating diverse AI agents, this research proposes a robust data model in a mathematical abstract form, standardizing data representation while enhancing the efficiency and reliability of AI-driven interactions across decentralized networks. The thesis not only identifies key challenges and opportunities at the intersection of AI and distributed ledger technologies but also offers a practical, scalable solution with significant implications for the advancement of the field. Through comprehensive theoretical and experimental investigations, it lays a foundation for future research and development in decentralized AI systems.

Publications

The work presented in this thesis is further supported by the authors' contributions to the field, which are highlighted through several publications. These publications showcase the development of ontology-based models, decentralized systems, and blockchain technologies, as outlined below:

Journal Articles

1. **Tara, A.**, Turesson, H. K., Natea, N., & Kim, H. (2023). ***An Evaluation of Storage Alternatives for Service Interfaces Supporting a Decentralized AI Marketplace***. IEEE Access. IEEE.
2. **Tara, A.**, Turesson, H. K., & Natea, N. (2024). ***Dynamic Storage Optimization for Communication between AI Agents***. Future Internet, 16(8), 274. MDPI.

Conference Proceedings

1. **Tara, A.**, Ivkushkin, K., Butean, A., & Turesson, H. (2019). ***The Evolution of Blockchain Virtual Machine Architecture Towards an Enterprise Usage Perspective***. In Software Engineering Methods in Intelligent Algorithms: Proceedings of the 8th Computer Science On-line Conference 2019, Vol. 1 (pp. 370–379). Springer.
2. **Tara, A.**, Butean, A., Zamfirescu, C., & Learney, R. (2020). ***An Ontology Model for Interoperability and Multi-organization Data Exchange***. In Computer Science On-line Conference (pp. 284–296). Springer.
3. Butean, A., Pournaras, E., **Tara, A.**, Turesson, H., & Ivkushkin, K. (2020). ***Dynamic Consensus: Increasing Blockchain Adaptability to Enterprise Applications***. In Computer Science On-line Conference (pp. 433–442). Springer.
4. **Tara, A.**, Taban, N., Vasiu, C., & Zamfirescu, C. (2021). ***A Decentralized Ontology Versioning Model Designed for Interoperability and Multi-organizational Data Exchange***. In Computer Science On-line Conference (pp. 617–628). Springer.
5. **Tara, A.**, Taban, N., & Turesson, H. (2022). ***Performance Analysis of an Ontology Model Enabling Interoperability of Artificial Intelligence Agents***. In Computer Science On-line Conference (pp. 395–406). Springer.

Research Objectives

The primary objectives of this research are:

- **To explore novel methods and techniques for enhancing the interoperability of AI algorithms within decentralized blockchain ecosystems:** This objective addresses key challenges in communication and interoperability by developing decentralized communication protocols that enable AI agents to collaborate effectively across multiple blockchain layers.
- **To investigate an ontology-based system for enhancing AI agent interaction in decentralized networks:** The research aims to create a multi-layered ontology model that facilitates seamless communication and data exchange among diverse AI entities within decentralized networks.
- **To examine decentralized security protocols and virtualized execution environments:** The study investigates decentralized key management, homomorphic encryption, secure computation methods, and virtualized environments such as KATA Containers, SCONE, and Trusted Execution Environments to enhance the scalability and security of AI applications.
- **To research a decentralized ontology versioning model for multi-organizational data exchange:** This objective details the architecture, data management, voting system, and consensus mechanism of a decentralized ontology model designed to support the interoperability of AI algorithms within distributed ledger technology systems.
- **To evaluate the performance of the proposed model:** The research assesses the model's efficiency through benchmarks and comparative analyses, focusing on data format compatibility, agent interaction efficiency, and environmental adaptability, demonstrating the model's effectiveness in enabling AI-driven tasks within decentralized networks.

Methodology

This research adopts a systematic approach to tackle the challenges of AI interoperability within decentralized blockchain networks. The methodology is structured into distinct phases, each contributing to the development and validation of the proposed solutions:

- **Literature Review:** The study begins with an extensive review of existing AI integration methods in decentralized networks, highlighting the limitations of current identity management systems, secure computation techniques, and decentralized storage solutions. This review forms the foundation for identifying gaps and guiding the development of novel approaches.
- **Ontology-Based Model Development:** A central component of the research involves designing a multi-layered ontology model aimed at standardizing data exchange formats and facilitating seamless communication between AI agents across diverse blockchain environments. This ontology-based system is meticulously crafted to ensure semantic compatibility and efficient data sharing among heterogeneous AI entities.
- **Decentralized Ontology Versioning Model:** To support multi-organizational data exchange, the research develops a decentralized ontology versioning mechanism. This model integrates a voting system and consensus protocol to manage version control, ensuring that AI agents operate harmoniously within decentralized ecosystems.
- **Evaluation of Virtualized Execution Environments:** The study critically evaluates virtualized execution environments, including KATA Containers, SCONE, and Trusted Execution Environments, to determine their effectiveness in enhancing the scalability and security of AI applications within decentralized networks.
- **Performance Benchmarking:** Rigorous performance benchmarks are conducted to assess the proposed model, focusing on key metrics such as interoperability, data format compatibility, and interaction efficiency. These benchmarks provide empirical evidence of the model's capability to improve the operational performance of AI agents in decentralized ecosystems.

This methodology integrates theoretical insights with empirical validation to deliver a robust and scalable solution for enhancing AI interoperability in decentralized blockchain networks. By systematically addressing the identified challenges, the research aims to bridge the gap between AI and blockchain technologies, paving the way for more adaptive and collaborative decentralized applications.

Proposed Model

This research introduces an ontology-based data exchange protocol designed to facilitate consistent communication between distributed software agents within a multi-organizational environment. The protocol comprises interoperable ontology models that represent the inputs and outputs of the agents, serving as a translator to harmonize diverse semantics, contexts, and data interpretations across different organizations, thereby enhancing both internal and external collaborations.

Unlike previous approaches that relied on monolithic and rigid ontology schemas, the proposed model adopts a multi-layered architecture to increase flexibility and decentralize storage structures. Each layer of the architecture consists of machine-readable semantic data structures that provide context for specific ontology dimensions, allowing data to be utilized, deployed, and updated in a decentralized manner.

The architecture is structured into the following layers:

- *Structural Layer* - Defines the formal specifications of the ontology, including classifications, concepts, properties, and relationships.
- *Connection Layer* - Manages information about concept locations and mappings between different ontology versions, whether internal or external.
- *Encoding Layer* - Specifies the encoding formats, such as UTF-8 or ISO.
- *Defaults Layer* - Provides fallback values for specific properties within the ontology.
- *Validation Layer* - Establishes formal validation rules for individual schema properties.
- *Restriction Layer* - Contains contextual restrictions based on schema properties.
- *Naming Layer* - Tags schema elements with human-readable identifiers.
- *Instruction Layer* - Offers guidance on how users should specify input data.
- *Versioning Layer* - Includes community proposals and details regarding schema structure changes and future evolution.
- *Template Layer* - Allows for contextual partitioning of schema elements.

The core layers focus on storing machine-targeted semantic information essential for operational purposes, while the optional layers provide supplementary human-readable information that aids in human-computer interactions. The ontology is deemed comprehensive when it encompasses all the necessary data details required for machine operations.

From an infrastructure standpoint, the ontology schema is replicated across the decentralized network, ensuring rapid availability to all AI agents functioning within the multi-organizational ecosystem. The multilayered architecture supports the ongoing evolution of the ontology through a robust versioning mechanism. Organizations can propose changes to any ontology layer, facilitating the modification of concepts, classifications, and schema structures.

Change requests are managed through blockchain technology, which ensures trust, security, and transparency in the storage and management of ontological data. A decentralized voting system allows stakeholders to collectively decide on modifications, with conflicting proposals resolved through community consensus, shaping the future evolution of the ontology. This approach ensures that the ontology remains adaptable, reliable, and responsive to the needs of a decentralized, multi-organizational AI environment.

Algorithms Composition

The proposed model not only enhances cross-organizational interoperability by defining standardized ontological data structures but also ensures consistency and uniformity within decentralized systems. By treating AI algorithms as modular, independent entities, the model facilitates their integration into complex solutions through well-defined data contracts at the algorithm boundaries. Utilizing the gRPC protocol, it supports remote execution and seamless communication between AI systems, enabling efficient interaction across different organizational contexts.

This architecture allows for the combination of multiple AI algorithms—such as those for skill matrix generation, language translation, and task management—to collaboratively address complex tasks like resource allocation in multinational companies. By leveraging these modular AI components, the model enhances operational efficiency and fosters collaborative AI-driven solutions in decentralized environments.

Dynamic Consensus

This research introduces also the the Dynamic Consensus model, which integrates multiple consensus algorithms on a single platform, allowing enterprises to customize mechanisms based on specific needs. Unlike traditional static models such as PoW, pBFT, and PoS, Dynamic Consensus provides adaptability, enabling various consensus rules to operate simultaneously to optimize performance in large, federated business consortia.

The model uses indexing functions to classify transactions and assign them to the most suitable consensus mechanism based on predefined parameters, enhancing scalability and processing efficiency. This hierarchical structure allows local transactions to be managed effectively while supporting broader, cross-entity consensus, which is crucial for complex enterprise applications.

Dynamic Consensus addresses the limitations of static algorithms by offering adaptive rules, improved parallelism, and a structure that separates machine-to-machine and business consensus, facilitating scalability and enhancing cross-organizational collaboration in large-scale blockchain networks.

Model Evaluation

The proposed ontology-based system for enhancing AI agent interoperability within decentralized blockchain networks was rigorously evaluated through a series of benchmarks and performance analyses. The findings highlight key contributions and advancements:

- **Enhanced Interoperability:** The multi-layered ontology model significantly improved communication efficiency between AI agents across various blockchain layers. High data format compatibility and precise semantic alignment facilitated effective cross-system data exchange, greatly enhancing overall interoperability.
- **Adaptability and Scalability:** The system demonstrated robust adaptability across diverse decentralized environments, maintaining performance and accuracy across multiple blockchain protocols. It efficiently scaled with increased network sizes and agent interactions, showing minimal latency and optimized resource use.

- **Flexible Data Formats and Agent Interaction:** The model's flexible data format supports a wide range of data types, enabling smooth communication between AI agents. Optimized interaction protocols enhanced flexibility and scalability, allowing seamless agent interactions in complex environments.
- **Environmental Robustness:** Performance evaluations across various computational environments confirmed the model's adaptability to different network latencies and resource conditions, reinforcing its reliability in decentralized systems.
- **Optimized Algorithms and Execution Environments:** The architecture and algorithms were tailored for modularity, speed, and accuracy, supporting concurrent operations among multiple agents. Optimized execution environments further improved system reliability and performance.
- **Decentralized Storage Technologies:** The evaluation of decentralized storage solutions, including P2P networks and public and private blockchains, demonstrated their effectiveness in managing large datasets for AI agents, enhancing the model's efficiency and security.

The evaluation confirms that the proposed ontology-based model significantly enhances interoperability, scalability, and security of AI algorithms within decentralized blockchain networks. By leveraging structured data formats, adaptive communication protocols, and secure data handling, the model advances the development of collaborative AI-driven applications, marking a critical step forward in decentralized AI systems.

Conclusions

This research addresses the critical challenges of integrating AI algorithms with decentralized blockchain networks by introducing a multi-layered ontology-based system that enhances interoperability and communication among AI agents. The proposed model standardizes data representation, enabling seamless communication across heterogeneous systems and serving as a robust foundation for developing advanced decentralized applications.

The key contributions of this work include the development of a multi-layered ontology that facilitates efficient communication between AI agents, significantly enhancing interoperability across decentralized environments. The model's scalability has been rigorously tested, demonstrating its ability to support large numbers of AI agents without compromising performance. Furthermore, the framework's adaptability to varying environmental conditions allows AI agents to dynamically adjust their operations, ensuring stability and efficiency within decentralized systems.

The implications of this research are far-reaching, particularly in sectors such as finance and healthcare, where the integration of AI with blockchain technologies can enhance security, streamline operations, and improve overall system efficiency. By bridging the gap between AI and blockchain, this study not only advances the field of decentralized AI networks but also provides a scalable and adaptable framework for future innovations in secure, collaborative AI-driven applications.