A Blockchain-based, Semantically-enriched Software Framework for Trustworthy Decentralized Applications

Thanasis G. Papaioannou[1], Petar Kochovski[2], Klevis Shkembi[2], Caroline Barelle[3], Anthony Simonet-Boulogne[4], Marco Ciaramella[5], Alberto Ciaramella[5], and Vlado Stankovski[2]

[1] Athens University of Economics & Business (AUEB), Greece pathan@aueb.gr
[2] University of Ljubljana, Slovenia
{petar.kochovski,klevis.schembi,vlado.stankovski}@fri.uni-lj.si
[3] European Dynamics, Luxembourg caroline.barelle@eurodyn.com
[4] iExec SARL, Lyon, France asb@iex.ec
[5] IntelliSemantic srl, Rivoli, Italy
{marco.ciaramella,alberto.ciaramella}@intellisemantic.com

Abstract. Multiple threats have been identified when citizens interact with online services such as unknown provenance of information, unknown quality of service providers, spread of fake news, fraud, personal privacy violation, centralisation of power to name a few. Blockchain has been considered as key technology to address many of these challenges; however, in reality, building trustworthy decentralized applications (Dapps) is not straightforward as much blockchain-based functionality needs to be developed from scratch and combined with data semantics. In this paper, we propose a new software framework, namely ONTOCHAIN, that leverages semantic web and blockchain technology to build, as distinct value for the Next Generation Internet, fundamental support for trustworthy data/services exchange and trustworthy content handling. It comprises a novel protocol suite grouped into high-level application protocols, such as data provenance, reputation models, decentralised oracles, market mechanisms, ontology representation and management, privacy aware and secure data exchange, multi-source identity verification, value sharing and incentives, and lower-level core protocols that include authorisation, certification, privacy-aware data processing, cross-chain gateways, identity management, secure data exchange, and data semantics in smart contracts. We demonstrate that these protocols are already available and combined to implement interesting NGI Dapps.

Keywords: trust, service exchange, content handling, Dapps

1 Introduction

Nowadays, the boundaries between the digital life and the physical world are almost non-existent. This allows, various entities (e.g. governments, companies and citizens) from all over the world to participate in knowledge generation and exploitation like never before. However, when it comes to knowledge exchange, the Internet cannot guarantee that bias or systematic abuse of global trust are avoided. The concentration of information into the hands of few big providers of Internet services, puts individuals at risk of being presented partial or biased information reflecting the provider's viewpoint. Digital trust is a necessity in such a world reliant on ever-increasing connectivity and data use.

The "Contract for the Web" [6] introduced by the World Wide Web Foundation led by Sir Tim Berners-Lee [2] presented a global action plan to save the web from manipulation, privacy violations, false information, fraud and other threats to Internet users. Blockchain technology is deemed by many as the holy grail for building future Next Generation Internet (NGI) decentralized applications (Dapps) towards decentralization of power and knowledge, trustworthy transactions, enhanced privacy and higher security in online interactions. However, it lacks data semantics, while it currently necessitates big development efforts to build complete end-to-end trustworthy Dapps from scratch.

In this paper, we overview an innovative software framework for trustworthy decentralized applications (dApps), by integrating blockchain and semantic technologies, which is being collectively built by a large community in the ONTOCHAIN ecosystem[7]. This software framework and platform enables the development and deployment of trustworthy Dapps for various domains, such as eScience, eEducation, eHealth, eGovernment, eCommerce, eTourism, eInfrastructures, etc. We provide an insider's comprehensive look to the ONTOCHAIN software framework, the services and functionality that it offers, and explain how it can disrupt the development of innovative Dapps. Finally, we demonstrate the offered functionality of our software framework with instances of materiarized Dapps that integrate it.

The remainder of this paper is organized as follows: Section 2 describes the state of the art and how ONTOCHAIN advances it. Section 3 presents an overview of the ONTOCHAIN platform, its architecture and its overall design. Section 4 describes the semantic data management within ONTOCHAIN. Section 5 and Section 6 describe functionalities and services of our software framework. Section 7 showcases innovative integrated Dapps hosted on the platform, and Section 8 concludes our work.

2 Related Work

A number of blockchain frameworks that provide flexible and adaptable solutions serving different applications have been proposed, such as Hyperledger Fabric [6], Ethereum [3], R3 Corda [7], Tezos [1], EOSIO [12] and Ontology [13]. These platforms allow the execution of *smart contracts*, i.e., self-executing decentralized programs that can read and write the state of the blockchain on top of which they are deployed. Smart contracts [4] enable the specification of advanced logic

[6] `https://contractfortheweb.org/`
[7] `https://ontochain.ngi.eu/`

and the automation of business workflows, thus allowing for the implementation of Dapps in different domains.

Hyperledger Fabric [6] has been built as a scalable, modular architecture with specific industrial use cases in mind, such as loan application, post-trade management in finance, credentials of physicians in healthcare, portable identities and supply chain management. It offers three different libraries for identity management, for executing smart contracts and implementing new smart contract languages, as well as for cryptography. Unlike Hyperledger Fabric, Ethereum is not that modular, but offers a generic platform for hosting all kinds of transactions and applications. Ethereum executes random complexity codes through its EVM and is freely available without authorization to any person (in one term, "permissionless"), as opposed to Hyperledger Fabric that is permissioned. While Ethereum might have the largest developer community with lots of open-source code (comprising mostly of monolithic solutions built from scratch), no running services or libraries actually exist for facilitating the development of new functionality or Dapps. The main use cases of Corda [7], which is a permissioned blockchain, are drawn from the financial services industry, although it claims support for Dapp development of broader scope. Corda is a decentralised global database, which offers support for identity and token management. EOSIO [12] is designed for enterprise-grade use cases and built for both public and private blockchain deployments. The EOSIO platform provides functionalities, such as accounts, authentication, databases, asynchronous communication, and the scheduling of applications across multiple CPU cores and clusters. The Tezos platform [1] is open-access and it provides support for Dapp development by means of comprehensive documentation, smart contract programming in Python or Ligo (with various syntax), smart contract archetypes for formal verification and libraries for writing smart contracts in different languages. The Ontology multi-chain and multi-system blockchain framework [13] offers a number of universal modules for Dapp development, such as the Distributed Identity Framework (DID), the Distributed Data Exchange Framework (DDXF) and ontology oracles.

However, all aforementioned blockchain platforms offer either limited or low-level functionality for Dapp developers, while they are almost agnostic towards ontologies and semantic-data management, as opposed to ONTOCHAIN.

3 The Ontochain platform

For enabling modularity, scalability, openness and high performance, the ONTOCHAIN platform comprises bottom-up: (1) the distributed ledger technologies layer, where the smart contracts of the various services are deployed, (2) the core protocols layer, where fundamental functionality for building Dapps resides, (3) the application protocols layer where more application-specific functionality resides, the ontologies layer that defines data semantics employed in all aforementioned layers and (4) the applications layer, where Dapps reside combining

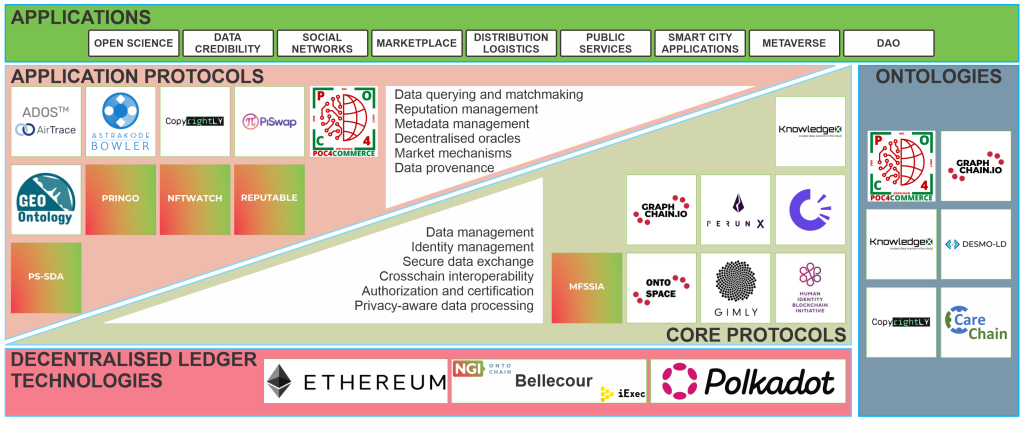


Fig. 1: The ONTOCHAIN high-level architecture.

functionality from the previous layers. This software framework and platform is depicted in Fig. 1. In the sequel, we describe each layer in detail.

Ethereum VM was chosen as a basis platform, since it has the largest developer base. SCs deployed on Ethereum can directly call other SCs implementing services or communicate to external data services through oracles. REST APIs are offered by all off-chain ONTOCHAIN web services. Web3 Dapps can implemented by directly employing or combining SCs and REST web services. A production-grade physical infrastructure where all ONTOCHAIN functionality is currently being deployed is referred to as Bellecour. Bellecour is a Besu-based PoA blockchain network also used by iExec for production purposes. Future ONTOCHAIN functionality will also be offered atop of this platform.

4 Ontologies

The Ontologies layer enable management and exploitation of web ontologies within the ONTOCHAIN ecosystem. Ontologies that support e-commerce transactions in the blockchain domain have been developed in our software framework by ONTOCHAIN-funded *POC4COMMERCE* project[8]. Three baseline ontologies were developed: (1) OC-Found, based on the OASIS ontology, to allow semantic description of stakeholders in the ONTOCHAIN ecosystem, including supply chains, digital identities of agents, etc.; (2) OC-Commerce, based on the GoodRelations[9] ontology, to allow semantic description for auctions and commercial activities; (3) OC-Ethereum, based on the BLONDiE [8] ontology, for semantic description of Ethereum blockchain, smart contracts and tokens. A high-level view of the OC-found ontology is depicted in Fig.2. This ontology can be used to define metadata of deployed services and smart contracts in the ONTOCHAIN platform, so that they become indexable and discoverable by the

[8] https://ontochain.ngi.eu/content/poc4commerce-practical-ontochain-commerce

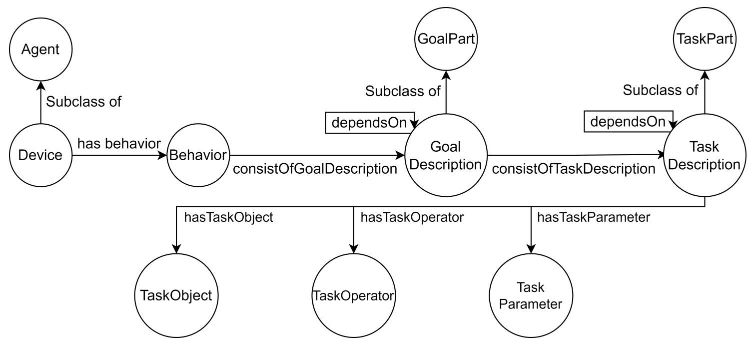


Fig. 2: Ontological Schema of agent behaviors.

search engine provided by POC4COMMERCE. Moreover, this ontology can be used to facilitate interoperability across cross-services communication within the ONTOCHAIN ecosystem and with external services.

This functionality is central to ONTOCHAIN and facilitates development. A low-code IDE for developing smart contracts has been developed by the ONTOCHAIN-funded *Bowler* project [10]. Smart contracts can be converted into RDF blueprints and stored in the system. Standard ontologies for different knowledge domains are employed for smart-contract development, however the IDE allows the development of new ontologies. The IDE enables semantic queries into semantically enriched smart-contract blueprints for facilitating development.

What is the value of these semantically-enriched oracles for dapp developers? Semantically-enriched distributed oracles system has been developed by ONTOCHAIN-funded *DESMO-LD* project[9], with particular focus on Web-of-Things (WoT) ontology to allow interoperable communication between heterogeneous IoT systems and large number of devices. It includes support for spatial queries based on WoT ontology metadata.

Modeling NFT data into a semantic graph has been developed by the ONTOCHAIN-funded *NFTWatch* project[10]. It defines a new ontology for annotating all NFT properties, especially related to trustworthiness/confidence, and combines it with existing ontologies, namely FOAF, cidoc-crm, DBpedia, VIVO and Event.

To facilitate data copyright management, the Copyright Ontology has been developed by ONTOCHAIN-funded *CopyrightLY* project. It includes several models: (a) creation (the different shapes of copyright creations along their lifecycle), (b) rights (legal constructs regulating what actions are favored or restricted) and (c) actions (modelling where copyright actions moving creations along their lifecycle).

In this section, we can add the ontologies developed from Recheck Green Box and OTCnLNG projects.

[9] `https://ontochain.ngi.eu/content/desmo-ld`
[10] `https://ontochain.ngi.eu/nftwatch`

5 Core Protocols Layer

5.1 Identity Management

A self-sovereign identity (SSI) solution based on P2P communication that brings trust and usability to users without compromising security and privacy of the ecosystem and its members has been built by the ONTOCHAIN-funded *Gimly* project. It is an interoperable solution, which is compliant with W3C decentralised identities (DID) and verifiable credentials (VC) standards. It allows end-users to authenticate themselves and present claims directly to the several parties, without the necessity to rely on a third-party identity provider. The solution is implemented with the Ethereum DID method, but is designed to be easily integrated with other DID methods or blockchain networks.

Also, an SDK to link DIDs, SSIs and VCs with real-world identities has been developed by the ONTOCHAIN-funded *HIBI* project. eIDAS[11] standard is employed for qualified electronic signatures, which requires NFC scans of legal EU identification documents. With HIBI, developers can: (1) support eID-based authentication in their applications; (2) let users sign transactions and documents using their physical eID card; (3) link the legal identity of a user to a blockchain-based public key; (4) perform key backup and recovery using a legal ID document.

5.2 Authorization, Certification

For user authorization, a *multi-challenge authentication solution* has been developed by the ONTOCHAIN-funded *MFSSIA* project[12]. It applies a risk assessment method to Multi-Factor Authentication (MFA) in the Authcoin protocol[13] to enable a trusted semantics-driven Internet marketplace. It provides self-sovereign flexibly configurable multi-factor challenge-set based identity authentication for secure, trusted and repudiation-checking engagement of humans and machines in e-market transactions in the M2X economy. Moreover, it provides APIs for loosely coupling with other ONTOCHAIN projects that address also identity management, such as *Gimly* and *HIBI*.

5.3 Semantic Data Management

The semantic data management has been provided by two ONTOCHAIN-funded *GraphChain*[14] and *Ontospace*[15] projects. Decentralised on-chain graph management technologies has been implemented [14]. Instead of encapsulating the semantic data into blockchain blocks, Blockchain mechanisms on top of semantic data have been implemented, allowing functionalities such as: (1) hashing

[11] `https://digital-strategy.ec.europa.eu/en/policies/discover-eidas`
[12] `https://ontochain.ngi.eu/content/mfssia`
[13] `https://authcoin.com/`
[14] `https://ontochain.ngi.eu/content/graphchain`
[15] `https://ontochain.ngi.eu/content/ontospace`

of subgraphs for the on-chain graph structures; (2) procedural smart contracts with access to the on-chain semantic data; (3) identification, authorisation and data provenance for the on-chain data; (4) sharding mechanisms and strategies. Multiple sidechains correlated to an overarching or external parent-chain, responsible for exposing activities with respect to their timing, external access and storing large ontologies as graphs have been created. The solution delivered by *GraphChain* and *Ontospace* are based on a modified Ethereum client, which has made it possible to achieve an oracle-less state by creating an ecosystem of sidechains that are integrated with graph databases.

5.4 Privacy-aware data processing

Nowadays, data exchange is hampered by confidentiality requirements due to competitive (e.g., data cost) or regulatory (e.g., personal data) considerations. As a result, data scientists who are responsible for data processing, have to be employed in-house or are contractually restricted by non-disclosure stipulations, which tend to be ambiguous and costly to enforce. To address these issues, a privacy-aware data processing protocol has been developed by the ONTOCHAIN-funded *KnowledgeX* project[16]. It leverages technologies such as: blockchain and smart contracts, decentralised cloud computing, Trusted Execution Environments to preserve data privacy, and technologically guarantee contract fulfillment, so that confidential data is processed in secure enclaves based on smart-contract transactions without any data leakage. It also offers a marketplace for privacy-aware data analytics.

5.5 Secure Data/Knowledge Monetization and Exchange

While data marketplaces are very popular and multiple instances do exist, they mostly exchange raw data without any means for monetization of any data resale. The secure exchange of knowledge (i.e., semantic linked data) among different entities with appropriate means for knowledge monetization and management have been the focus of the ONTOCHAIN-funded *DKG* project[17]. Knowledge is indexed in a P2P network (OriginTrail Decentralized Network, i.e. ODN) and its hashes are recorded to external blockchains, e.g., Ethereum, Polkadot, xDai, for ensuring integrity. Knowledge Tokens are ERC-721 non-fungible tokens associated with data items for access control and data tradeability, which are stored within knowledge wallets following W3C DIDs and SSI framework regarding their management. Moreover, a Knowledge Marketplace is offered where knowledge tokens can be traded against other cryptocurrency or attract liquidity. Data buyers can create Knowledge Tenders for crowdourcing the aggregation of knowledge of specific key parameters. FairSwap approach [5], where a smart contract releases to the buyer the key to decrypt the transferred knowledge upon payment, has been implemented for secure knowledge transfer. Knowledge Tokens smart

[16] `https://www.knowledgex.eu/`
[17] `https://ontochain.ngi.eu/content/dkg`

contract API allows for minting of fungible (ERC-20) or non-fungible (ERC-721) tokens and their transfer. Knowledge Marketplace offers a REST API that includes methods for announcing knowledge availability, querying knowledge, or issue complains on the knowledge transaction, while Knowledge Wallet API contains methods for creating new or updating knowledge assets (and their semantic graphs), purchasing knowledge or tokenizing knowledge.

5.6 Gateways and Cross-chain Interoperability

An important obstacle to blockchain adoption is the increasing number of isolated/siloed application-specific blockchains that are meant to solve issues related to scalability and gas price. A secure, scalable and open interoperability framework for exchanging information, assets (including ERC-20 tokens) and arbitrary logic between heterogeneous blockchain ecosystems has been provided by the ONTOCHAIN-funded *Perun-X* project[18]. The solution relies on state channels to execute smart contracts off-chain safely in a network of nodes, and implements a liquidity manager for cross-chain transfers. While other solutions based on public connectors or blockchains-of-blockchains are often on-off solutions or require the blockchains on both ends of a transfer to implement a common protocol, *Perun-X* adopts a hybrid approach that makes it blockchain-agnostic. It also provides a feature-rich SDK for connecting client applications to the Perun network and enabling them to create, open and close channels.

5.7 Trusted and Confidential Computing

A decentralized marketplace for cloud computing where individuals, applications and smart contracts can execute off-chain applications with a very high level of trust and traceability is provided by iExec[19] to the ONTOCHAIN software framework. In a context where smart contracts are too slow and limited, and where off-chain information cannot be trusted, the iExec Marketplace provides blockchain properties such as trust, provenance and traceability when executing off-chain Dapps. iExec achieves these properties by delegating trust to Ethereum smart contracts and hardware-based Trusted Execution Environments (TEE), creating a computing platform that cannot, by design, violate the agreements that are recorded in smart contracts. Blockchain-based decentralised and confidential computing can be leveraged in a number of applications, such as decentralized oracles, privacy-preserving computing and Self-Sovereign Identities. These features are provided to all ONTOCHAIN applications and services through an SDK and a set of high-level APIs.

[18] `https://ontochain.ngi.eu/content/perun-x`
[19] `https://iex.ec/`

6 Application Protocols Layer

6.1 Decentralized Reputation Management

Reputation mechanisms can be utilised as tools to estimate the trustworthiness of service providers and other participants in the ecosystem. The ONTOCHAIN decentralized reputation management that is delivered by the ONTOCHAIN-funded *Reputable* project[20], allows cross-platform privacy-aware reputation system which leverages Blockchain technology to achieve decentralised, verifiable calculation of reputation scores. Moreover, it enables interaction with end users and systems through a secure, reputation dashboard to facilitate user verification as seamless integration with other systems and services. The reputation score is calculated based on unlinkable user feedback for smart-contract transactions.

6.2 Services Directory, Querying and Matchmaking

An application protocol that extends the most representative ontologies and allows representation of today's blockchain-oriented e-commerce has been developed by the ONTOCHAIN-funded *POC4COMMERCE* project[8]. *POC4COMMERCE* reuses and extends ontologies, such as OASIS [11] to describe commercial participants and smart contracts, GoodRelations [9] to describe commercial offers, and BLONDiE [8] to descibe Ethereum nework's essential components. To expose its functionalities to the ONTOCHAIN ecosystem, POC4COMMERCE delivers a set of interfaces that allow communication with three modular ontologies describing each semantic compartment of eCommerce, from participants, assets, and offerings, to supply chains, smart contracts, and digital tokens. The ontological stack is released together with SPARQL queries implementing the defined competency questions.

6.3 Decentralized Oracles

Decentralised Oracles are gateways that allow smart contracts to interact with the outside world whilst maintaining high security and privacy standards. *ADOS* delivers an ontological-based oracle solution that prevents corruption and tampering threats in IoT applications. It allows quantifying the quality and the reliability of data before injecting it into the Blockchain. For each sensor device, *ADOS* builds a graph embedding based on a Graph Neural Network model and uses it to perform anomaly detection in the raw measurements. In addition to the sensed data, it also pushes an associated Data Quality Factor (DQF) to the blockchain for future audits. The model is run on top of the iExec trusted computing platform in order to certify the computed DQF value with Trusted Execution Environments (TEE).

A decentralized oracle system to reliably consume IoT data from on-chain smart contract and provide trustable means to include real world effects by using

[20] `https://github.com/ONTOCHAIN/REPUTABLE`

attenuation APIs is developed by the ONTOCHAIN-funded project *Desmo-LD*. This project leverages on Web of Things (WoT) interaction model and WoT ontology for implementing an interoperable connection layer with heterogeneous IoT systems and devices. Specifically, the devices are brought into the oracle network through specialized nodes of Things Description Directories (TDDs): their job is to resolve the queries from clients in exchange for a reward in tokens and to perform data quality control.

Geontology [21] addresses geolocation as part of the semantic capabilities to empower any transaction. An algorithm focused on data geolocation and access control called Proof of Offset (POO) has been designed and developed. This innovative protocol POO enables higher data access control by geolocation, accountability and data exposition minimisation.

6.4 Data Provenance

An application protocol that allows management of ownership and copyrights has been developed by the ONTOCHAIN-funded *CopyrightLY* project. It proposes a system capable of rooting on-chain copyright transactions, especially NFTs, on copyright claims that can by tied to evidence and legally validated. A set of smart contracts allow registering Manifestations (i.e. authorship claims), Complaints (i.e. denouncing authorship claims) and Reuses (i.e., setting reuse terms to a manifestation, including the initial offer, the negotiation steps and the final reuse agreement). Also, CopyrightLY uses semantic technologies and the formal conceptualizations provided by the Copyright Ontology that contributes towards the interoperability of the copyright data.

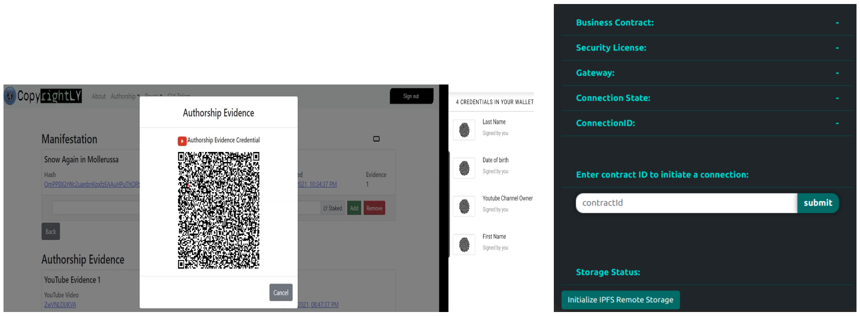
6.5 Market Mechanisms

Price Determination The current NFT Market often shows an imbalance of power in transactions causing market failure in the worst case. There is a lack of transparency in regard to price building and quality. ONTOCHAIN-funded PiSwap project[22] delivers a market-mechanism (i.e. the Bull-Bear-Certificate) that distributes an automated market maker model for digital assets with an automated liquidity providing. In these market-mechanism, investors can bet on the price of an underlying digital asset, e.g. NFT, using Bull and Bear counterpart certificates. These certificates are fungible and can be swapped with an ETH liquidity pool.

Public Goods Creation - Game NFTs Building public goods entails the problem of *free riding*, i.e., exploit the public good without contributing. A platform that implements an economy for funding and curating public goods, be it forest plantation, wildlife protection, etc., was created by ONTOCHAIN-funded *PRINGO* project. It connects the creation of public goods to the video gaming industry, being a huge, growing industry (approaching $200Bn revenues in 2021).

[21] `https://github.com/ONTOCHAIN/geontology`

[22] `https://ontochain.ngi.eu/content/piswap`



(a) *Gimly* and *CopyrightLY* integration (b) *MFSSIA* and *DKG* integration

Fig. 3: Screenshots from demos of *CopyrightLY* and *MFSSIA* projects.

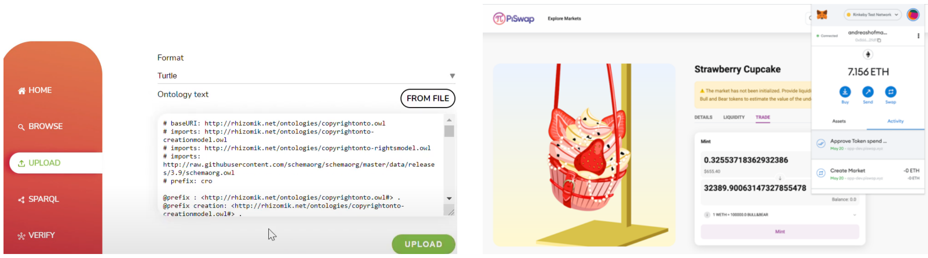
This service enables gamers to obtain direct profit from improvements of the real curated goods. It supports digital representation (or NFT minting) and dynamic updating properties changes of NFTs metadata of their real-world assets, and a decentralized governance layer that allows the definition and management of the rules for NFT trading and value sharing among different stakeholders (e.g., common goods curators and gaming companies).

NFT Semantic Markets From September 2020 to September 2021, the monthly NFT sales went from 4M USD to more than 2000M USD. ONTOCHAIN-funded NFTWatch project[23] allows tagging/annotating NFT and evaluating a score of trust/confidence, evaluating an NFT address confidence level, associated with advanced search functionalities. It offers a fully working on-chain/off-chain data collection engine (through different crawlers for the various NFT markets and automatically analyses the content of digital media provided (MLs based image classification) to extract NFT semantics and assign confidence score, stored in Neo4j and available for querying via a REST API.

7 Demonstration

In this section, we showcase a few out of many interesting integrated applications of ONTOCHAIN functionality. The demo[24] from *Gimly ID* shows important functionality of this solution in the context of the *CopyrightLY*. The media resource with verified authorship with *CopyrightLY* is accessed by personal authentication with the *Gimly* ID wallet on a mobile phone: in such way, the personal authentication process is made by QR code processing (see Fig. 3a). The project *MFSSIA* uses decentralised knowledge graphs (*DKG*) to express challenges and contextual facts for response evaluation (see Fig.3b). The communication between *iExec* oracles and *DKG* test node is performed by the

[23] `https://ontochain.ngi.eu/content/nftwatch`
[24] `https://www.loom.com/share/d49e005bb32349d7950022e83d55b944`



(a) *Graphchain*/*CopyrightLY* integration (b) *NFTSwap* (Bull or Bear to Swap)

Fig. 4: Screenshots from demos of *GraphChain* and *NFTSwap* projects.

MFSSIA DKG rest client that is deployed to the AWS cloud. The functionality of *Graphchain* has been also demonstrated in the context of *CopyrightLY* (see Fig.4a). A demo[25] presents Ontohub portal and the use case of uploading, verifying CopyrightLY ontology and replicating among nodes. Finally, a demo[26] showcasing NFT transactions based on price determined by NFTSwap is shown in Fig.4b.

8 Conclusion

In this paper, we presented an overview of the ONTOCHAIN blockchain software framework. We described in high-level all existing functionality in the framework and provided adequate references. We also demonstrated some functionality. In the future, a number of interesting Dapps will be deployed on top of the ONTOCHAIN software framework, such as semantic digital logbooks for companies, building, etc., data credibility and fact checking for online content, decentralized trustworthy social networks, semantic energy data management, decentralized traffic management, trustworthy logistics/supply chains, remote working and presence including in the metaverse, fair and privacy -aware data/knowledge markets and healthcare data sharing. Also, new functionality will be added towards semantic cross-chain interoperability, more energy-efficient blockchain infrastructure, and automated semantic reasoning and matching.

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