IoT and NFT-based Asset Management System in Railway Maintenance

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Abstract

The railway industry is a sector where asset maintenance is paramount in ensuring passenger safety and service continuity. In this context, the application of the blockchain paradigm can represent an innovative and effective solution for improving railway maintenance efficiency. Specifically, blockchain can be used to record every event a railway asset encounters during its useful life cycle, including both the anomalies it has experienced and the maintenance cycles it has undergone. Through the use of technologies such as NFT tokens, IPFS, and IoT, it is possible to create a transparent, verifiable, and immutable railway maintenance management system. The assured on-chain recording of every event, combined with incentive mechanisms based on the distribution of native blockchain tokens, creates a virtuous cycle where maintainers are incentivized to complete all anticipated maintenance cycles to keep assets in optimal conditions. Furthermore, a secondary trade royalty system can be established by using NFT protocols, thereby creating additional incentive for the creation and maintenance of quality assets. This paper will examine the technologies used and methodologies adopted to implement this blockchain-based railway maintenance management system, with the aim of highlighting the main challenges and opportunities related to its implementation. Some case studies will also be analyzed, and potential future prospects for the use of blockchain in this sector will be discussed.

Keywords

Blockchain, IoT, Maintenance, Maintenance Management System (MMS), Railway, Rollingstock, Helium, Lora, LoraWan, NFT

1. Introduction

In recent years, we have seen an exponential increase in new technologies that have greatly impacted our daily lives. These services are constantly evolving and aim to provide more and better performance and functionality in fields such as telecommunications[1, 2, 3], artificial intelligence[4, 5, 6], transportation services[7], energy services[8, 9, 10, 11, 12], public administration[13], healthcare [14, 15, 16, 17, 18, 19] and so on. Consequently, it is essential to take into consideration the security of both users and system equipment while ensuring, at the same time, service continuity. The railway industry represents a sector in which passenger safety and service continuity are fundamental. To this end, asset maintenance constitutes an essential element. However, the constant monitoring of asset conditions and the implementation of preventive maintenance cycles require significant time and resources. In this context, the application of the blockchain paradigm can represent an innovative and efficient solution to enhance railway maintenance efficiency. Preventive maintenance constitutes a mitigation to the risk of asset safety levels degrading over time. Therefore, it is crucial to effectively track the implementation of maintenance cycles to ensure passenger safety and service continuity. The indelible and unalterable nature of blockchain guarantees the transparent and verifiable storage of all information related to an asset's life-cycle, avoiding potential fraudulent management or information manipulation. To analyse the potential impact of applying blockchain to railway maintenance management, we adopted an approach based on a review of the existing literature, analysis of case studies already present in the literature, and our direct experience in the field. Based on the extensive experience gained in the railway maintenance sector, acquired thanks to active participation in various railway projects, including those of maintenance management, we have identified the following potential areas of improvement in railway maintenance management:

- **Communication Infrastructure:** "Live" data collection pertaining to the status of assets located in remote locations and rolling stock distributed over a wide geographical area, including diagnostic alarms, values related to asset usage metrics, and the location of the asset itself.
- **Licence Costs**: the management of maintenance through decentralised storage technologies allows for the reduction in costs related to database licences and service fees for MMS (*Maintenance Management System*) platforms.
- **Time to Market:** improvement in the implementation and release timings of maintenance management systems from when they are first conceptualised to when they are actually rolled out to the on-site maintenance teams.
- **Technical Documentation:** simplification of access to technical documentation, configuration information, and, where applicable, asset control software by maintenance teams.
- **Event Logging:** foremost, immutable and certified recording of the anomalies that an asset has incurred, followed by the preventive and corrective maintenance activities carried out on the assets throughout their entire life-cycle.

Specifically, two case studies were analysed regarding the use of blockchain in managing the activities of corrective and preventive maintenance of railway assets, and in the geographical traceability of *Rolling Stock*.

Our work, in reference to the following papers under review [20], [21], [22], [23], [24], [25], [26] and [27], is distinct in its specificity of blockchain application, focusing on the creation of a blockchain-based railway maintenance management system. This system incorporates technologies such as NFT tokens, IPFS, and IoT to create a transparent, verifiable, and immutable system. Unlike other publications,

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which provide a general overview of blockchain application in broader sectors [28], our paper delves more deeply into specific case studies and the challenges associated with implementing blockchain technology in the railway industry, providing an in-depth technical analysis.

In summary, the added value of our paper lies in the specificity of the blockchain application in railway maintenance management, examining specific case studies and the challenges associated with technology implementation. Meanwhile, other publications focus on broader sectors such as logistics, supply chain, drug management, protection of digital assets, and intelligent transport without concentrating on a specific case.

The work described lays the groundwork for a "ready-to-use" solution, providing an effective methodology aimed at improving the safety, efficiency, and quality of railway maintenance

The paper is structured as follows: In Chapter 2, the technologies used in the study are described, introducing a multidisciplinary integration approach aimed at ensuring the reliability of the information supply chain. There is also a mention of the solution that will be demonstrated in the research. In Chapter 3, two case studies are presented for the digitisation of railway assets, one static and one dynamic. Additionally, the decentralised RailChain application for visualising digital asset information is described, including the "Live" status from various NFT HeliumAdapter sources, and the infrastructure of the experimental model. Chapter 4 is dedicated to the use of dynamic NFTs, discussing their benefits and limitations in the proposed solution, and highlighting the integration of IoT and blockchain technologies for the indelible recording of the usage status of assets and the challenges of implementation. A gradual approach to introducing blockchain technology by sector component manufacturers is also proposed. Finally, in Chapter 5, the conclusions are drawn and potential future developments are explored.

2. Technologies Used

The methodology used to apply the blockchain paradigm to railway maintenance management requires a multidisciplinary approach, which involves the integration of various technologies to ensure the reliability of the supply chain that manages the association of information automatically collected from the field and the information recorded by the maintenance team to railway assets. The proposed approach envisages the integrated use of three technologies:

- **IoT:** the Internet of Things (IoT) is a technology that allows for the connection and management of common use objects via a network, utilising sensors, actuators, and embedded devices. This is done with the aim of collecting and analysing data to support decision-making and control activities. The Helium network was used as the communication infrastructure, which is a low-power wireless communication network based on LoRaWAN technology. This allows for the creation of a network of IoT devices.
- **NFT:** an NFT, which stands for "Non-Fungible Token", is a unique and non-interchangeable type of cryptographic token that is used to represent the ownership of digital and physical assets. Each NFT is unique and cannot be replaced with another. This means that NFTs can be used to certify the authenticity and exclusivity of an asset
- **IPFS:** the InterPlanetary File System is a peer-to-peer distributed file system that allows for the permanent and secure storage and sharing of data, ensuring data traceability, verifiability, and immutability.

We begin by broadly outlining the solution, the feasibility of which we intend to demonstrate.

2.1. IoT

To address one of the challenges of "live" data collection related to the status of assets (mainly diagnostic alarms and information related to the usage metrics of the asset in question) located in remote locations or pertaining to rolling stock distributed over a wide geographical area, it is necessary to identify a communication infrastructure to complement and integrate with more traditional communication networks, such as Terrestrial Networks (TNs) and Non-Terrestrial Network (NTNs) [29]. The technology identified for this purpose is LoRaWAN [30], in its specific application integrated with the *Helium* protocol [31].

The *Helium Protocol* [31] is a protocol based on *Solana* blockchain [32], aimed at providing secure and low-cost wireless networks for IoT devices. A key feature of the *Helium Protocol* is its use of a decentralised architecture, which allows devices to communicate directly with each other without the need for a central authority or intermediary. This philosophy sets the Helium network apart from any other LoRaWAN network, as the elimination of a central authority makes the network more resistant to failures and less vulnerable to attacks.

Another important feature of the *Helium* protocol is its use of a token-based incentive system, which rewards users who participate in the network by deploying and maintaining it. This helps ensure that the network remains decentralised and robust, even as the number of devices connected to it increases. The *Helium* protocol, through its *Proof of Coverage* [33] consensus algorithm, allows devices to earn rewards for coverage and traffic transfer for other network devices. This ensures that devices with better coverage earn more rewards and contribute to ensuring good network coverage. The *Helium* protocol also aims to make it easier for developers to build and deploy IoT applications on the network. This is made possible through the use of a simple application programming interface (API) and a suite of open-source tools for developers. This is the tool used to build the necessary middleware to implement communication between physical assets and their digital counterparts through a platform of decentralised *Oracles* [34]. This platform allows smart contracts to access data external to the blockchain, enabling the receipt and transmission of information from reliable sources. Furthermore, the *Helium* network uses a unique frequency hopping scheme to avoid interference and maximise the use of available spectrum. This allows multiple devices to communicate simultaneously on the same frequency band without interfering with each other. This improves the overall coverage of the network and allows a greater number of devices to connect.

2.2. NFT

The proposed solution involves modelling the assets and the articles linked to them using the blockchain paradigm.

Therefore, the next step will be to define the criteria for modelling and digitising physical assets through NFT tokens.

From a practical perspective, we can say that the essential elements that constitute an NFT are as follows:

- *Token Identifier*
- *Contract Address*
- *Owner* of the Token
- *Metadata* associated with the Token

Metadata defines the actual content of NFTs with features, attributes, and addressing related to external content. *Metadata* is essentially a JSON file that contains at least the following information: a *description*, a *link* to the digital media representing the NFT and *characteristics*.

The proposed solution is implemented on the *Ethereum* blockchain [35] and specifically adopts the ERC-721 standard [36], the first formal NFT standard that has been widely adopted. A significant part of the standard is dedicated to describing the interface with the smart contract that an ERC-721 token must implement, but there is also a recommendation on the basic format of metadata. To describe all the peculiar *characteristics* of the railway asset, the attribute set outlined above has been extended with the following specific information to cover all the documentary and certification aspects related to the asset itself while maintaining compatibility with the standard:

- Asset type and encoding;
- Geographical position;
- Maintenance reports and operational conditions;
- Hierarchical relationships between assets;
- BIM models;
- Technical documentation.

The type of NFT to be used for modelling must take into consideration that an asset is not a static entity that remains unchanged over time, but on the contrary, it has a history that must be traced. It should be possible to store every maintenance intervention it will be subjected to and every potential move from when it is installed to when it is decommissioned. Therefore, its digital equivalent cannot be a simple static digital ownership certificate identified by a traditional ERC-721 token, but for its modelling, a dynamic NFT must be used. The smart contract that will implement its minting should therefore be written in such a way as to make public the methods that allow the modification of metadata linked to the generated token. The metadata will thus be structured to contain all relevant information related to the modelled assets and their evolution over time, such as: identification code, installation site, installation date, user and maintenance manuals, maintenance reports, links between assets and articles up to, where applicable, the software package installed on the asset or the information related to its configuration. This type of metadata will be manually modified over time by the maintenance managers, reflecting the changes in the asset's destination and the maintenance activities to which it will be subjected. However, there is another category of information that we want to include in the digital model, which is the aforementioned "live" information. The smart contract will be written in such a way as to implement the reading of this information through LoRaWAN devices interfaced with the field through digital, serial or TCP signals. Since this information is external to the blockchain, this operation will be carried out through an *Oracle*. To avoid overlapping and synchronising the management of this automatically acquired information with the information that is manually updated by the operators within the same metadata set, an ad hoc smart contract will be implemented that will manage a family of NFTs to model this functionality by associating a specific asset with a specific Helium device; these NFTs will be identified hereafter as *HeliumAdapter*. Each digital asset that wishes to associate "live" information will therefore have within its metadata the reference to one or more *HeliumAdapters*. In other words, the referenced adapters will be the "children" of the asset in question.

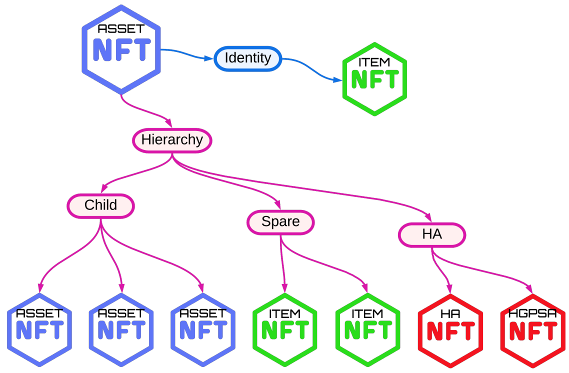

Figure 1: Asset relationship

The design of metadata is a crucial aspect for the representation of relationships that link *Assets* and *Items*. These relationships can be divided into two categories: identity relationships and functional hierarchical relationships. The identity relationship expresses the concept that an asset is nothing more than an instance of a specific item located in a particular location. This means that multiple assets can be linked by an identity relationship to the same item, for example, ten cameras of the same type A installed in different locations: "CAM-001", ..., "CAM-010" will be ten different assets linked to the same item "Type A Camera". Moving on to functional hierarchical relationships, these are of three different types (Fig.1):

1. Each asset can be functionally or physically linked to other assets, defined as *Child*.
2. Each asset can be linked to a list of items that represent spare parts of the same.
3. To each asset, one or more *HeliumAdapters* (HA), capable of providing "Live" information coming from the field, can be associated. The link can be related to the asset itself, its child assets, or some of its constituent parts.

To complete the picture, we can add a further modelling rule: all the above-mentioned relationships will be iterable at the *Asset* level.

2.3. IPFS

Given the substantial size of the information to be saved within the metadata, which is conditioned by the continuous growth throughout the useful life of the asset, storing the same *on-chain* was excluded a priori, and it was chosen to store them *off-chain*, registering on the blockchain only the reference URI to the data. For this purpose, the

IPFS system (*Inter Planetary File System*) [37] was identified, a distributed peer-to-peer protocol for securely and permanently exchanging data through a global network of interconnected nodes. In general, IPFS operates similarly to a blockchain-based node network, using a content-based addressing technique of the resource sought by the user, unlike conventional web access based on a specific address. That is, a unique CID identifier is assigned to each file, calculated cryptographically on its content, which acts as a permanent encoding of the file at that given moment. Once the file is uploaded to IPFS, it is immutable and will always be available at that reference. This characteristic means that every time the file describing an NFT's metadata is modified and uploaded to IPFS, it will be assigned a new CID since its content has changed, this CID will constitute the new reference URI. When an update request is made to the smart contract, the modification will be permanently recorded on the blockchain, ensuring the traceability of all changes made to the metadata. This approach can be extended to the storage of entire data structures and applied to the storage of folders containing management software, BIM models and maintenance reports, eliminating the need to implement parallel archives burdening local storage. Moreover, this solution allows avoiding the need to implement a system for tracking links between assets and local storage systems. This operating method allows for efficiently organising asset information, facilitating access by maintenance teams and avoiding duplications.

As for the metadata of the *HeliumAdapter*, a diametrically opposite design solution has been applied. For representational clarity, the image associated with the *HeliumAdapter* NFT will reflect the status of alarms and detected variables. To ensure the necessary flexibility, an alternative type of NFT is used, in which data is completely stored *on-chain* directly in the smart contract. Instead of a link, the *tokenURI* will contain a JSON-encoded data that includes extremely compact-sized graphical data in SVG format. The SVG vector graphic image is programmatically generated, encoded, and returned by the contract. Inclusion of the states detected by the LoRaWAN devices via the *Oracles* in the SVG makes the *HeliumAdapter* responsive to changes in both blockchain data and LoRaWAN devices.

3. Case Studies

For our paper, we will focus on two case studies. The first case concerns the digitisation of a high-criticality static railway asset, while the second case involves a dynamic asset, namely a *Rolling stock* that could be located over a wide geographical area.

3.1. Digitalisation of Static Railway Assets

Regarding the static asset, we will consider a structured asset consisting of a simplified version of a component subject to a high level of criticality that must meet very restrictive safety criteria: a cabinet that is part of the ventilation control system in a railway tunnel. This system is essential to ensure the safety of passengers and staff in case of fire. The ventilation system is used to dissipate smoke and hot air from the tunnel, in addition to providing fresh air during evacuation operations. The registration of regular preventative maintenance operations, of any anomalies that have occurred, and of subsequent corrective maintenance interventions is crucial to ensure that the system functions correctly in emergency situations. The asset is also associated with two NFT *HeliumAdapters* that model, respectively, a *Helium device* that implements Modbus RTU communication with the control Programmable Logic Controller (PLC) for the detection of anomalous conditions (for example, a Jet Fan inverter anomaly) and a *Helium device* that will detect anomalies related to the operation of the electromechanical components of the system (for example, intervention of auxiliary power circuit breaker) through digital inputs.

3.2. Digitisation of Dynamic Railway Asset

As for the dynamic asset, a Rolling stock simulation is modelled in a *Black box* mode by associating a digitalised asset with an NFT *HeliumAdapter*, which in turn models an *Helium device* designed to detect the asset's position via GPS. This will allow us to store real-time, permanent, and immutable information on the position and performance of the *Rolling stock*, such as speed, distance travelled, temperature, and energy consumption. This information could then be used to improve the safety and efficiency of the *Rolling stock*. For example, in the event of an accident, the performance information recorded on the associated dynamic NFT could be used to better understand what happened and how to prevent future accidents, optimise tram performance, and improve energy efficiency, or simply to schedule its inspection or preventive maintenance at the nearest depot.

3.3. Railchain Dapp

To conduct the analysis of results arising from the digitisation of assets through dynamic NFTs, it was necessary to develop a decentralised application (Dapp), named *RailChain*, with the functionality of an *Explorer* for digitised railway assets. This application acts as the *Front-end* for displaying all the information related to the digital asset, including the "Live" information status provided by various NFT *HeliumAdapters* associated with the assets. RailChain also allows us to browse the tree structure of the digitised *Product Breakdown Structure (PBS)* from the root element to the last LRU, being able to retrieve all the documentary information in support of maintenance activities. *RailChain*, through functions made available by commercial Web3 APIs, allows us to access and interact with the *Ethereum* blockchain. These APIs are used to read information on the blockchain, such as the list of all transactions, the content of a particular smart contract, or the content of metadata associated with a specific NFT token. The data received from the blockchain are then processed and presented in a *user-friendly* format using technologies such as HTML, CSS, and JavaScript. *RailChain*, acts as an *Application Server* to a client call in the following format:

https://www.cladiecar.com/railchain/?address=[NFTSmartContractAddress]&id=[ID_NFT]

The application returns the HTML page reporting all the information encoded in the metadata of the NFT described by the call parameters. The application is also capable of independently identifying whether the referenced NFT is an asset or a digital item, proposing the correct HTML page. In the returned HTML page, alongside each asset or item, the QR code encoding of the HTTPS call that returns its clear information is displayed. This solution aims to simplify the maintenance operations related to the asset, making it possible to access all the necessary information simply by

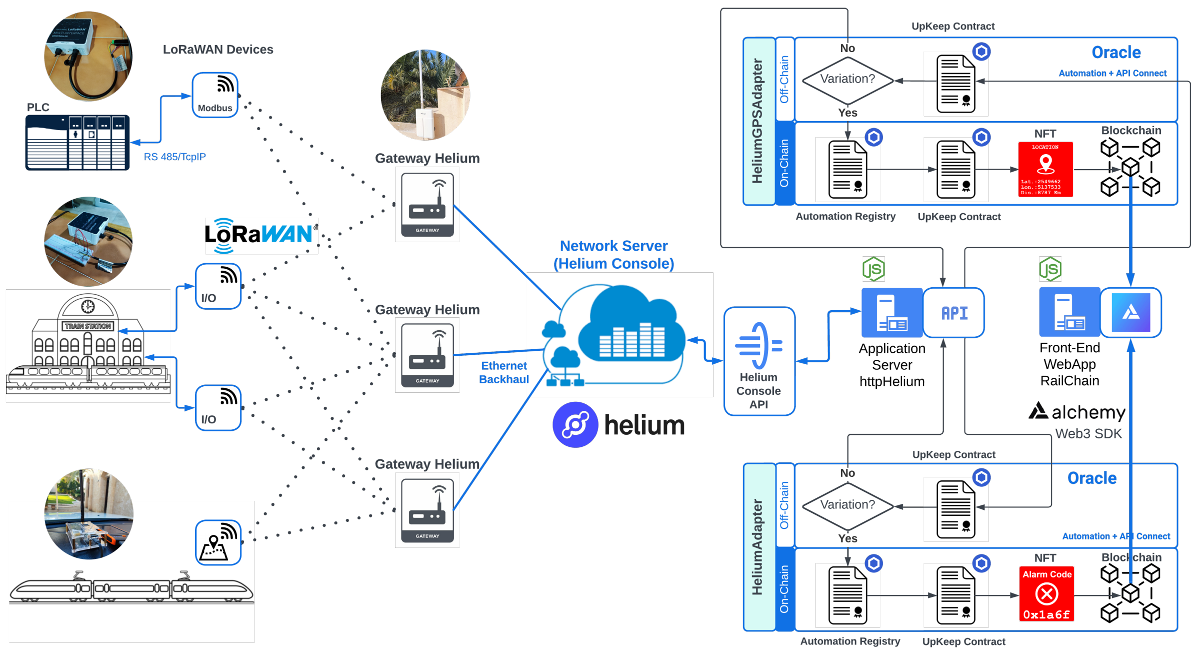

Figure 2: General architecture

scanning the QR code. In particular, the parameterised URL will also be used on the identification label to be applied to the physical asset installed in the field, ensuring a correct correlation between the digital asset represented by the NFT and the physical asset.

An additional feature of the interface is its ability to display the decoding of alarms and states received through the NFT *HeliumAdapter* associated with the asset. To simplify the interface and to draw the maintenance operator's attention only to active alarms, the following information will be displayed (Fig.3):

- Alarm message associated with the specific bit of the status word.
- Link button to the specific procedure to be followed for anomaly resolution.
- References to the asset subject to the anomaly, it could be the asset itself to which the *HeliumAdapter* is associated, one of its child assets (or in any case present in its descending hierarchy) or one of the items associated with it.

All the NFTs minted during the experiment can be viewed from any NFT *Marketplace*, with the limitation that only the main attributes, listed in the metadata attribute section, will be visible. In this particular case, since these are test NFTs minted on the Goerli Testnet, they can be viewed on the version of the "Marketplace" Rarible reserved for the Testnet: https://testnet.rarible.com/.

Applying all the criteria described so far, the assets defined in the case studies have been modelled, monitoring the various implementation phases through the web application *RailChain*. The model obtained shows a significant number of cases representing the different possible combinations of identity and hierarchy relationships. For immediate recognition of the type of digitised equipment, the convention was used to mint assets with a representative image having a blue background, while green was chosen as the background colour for the items.

Figure 3: Alarm management in RailChain

The digitisation of the physical asset was made possible through the writing of smart contracts, enabling the minting of NFT tokens in line with the ERC-721 standard. The dynamism of the digitised assets was achieved thanks to the update functions integrated into the smart contracts. This provided a degree of flexibility in managing attributes and documentation that proves maintenance carried out on the physical asset. All updates occur via transactions that are recorded in a certain and immutable manner on the blockchain. The update functions implemented in the smart contracts, in addition to ensuring the dynamism of the NFT tokens, are crucial in the design and fine-tuning phase of the digital asset, before its final release, making possible the correction or modification of metadata without proceeding to a new minting, and the simulation of digital assets behaviour in all possible operational situations.

This latter feature has been widely used throughout the implementation and testing phase, including the verification of asset integration with the NFTs of the *HeliumAdapter* family.

3.4. Experimental Model Infrastructure

To experiment with the solution described, a minimal infrastructure was set up by installing some fundamental elements based on the *Helium* technology (Fig.2).

Firstly, a *Helium Hotspot* was installed to create a private LoRaWAN network. This device allows IoT devices compatible with the LoRaWAN network to connect and transmit the collected data to the *Helium Console*.

Secondly, IoT devices compatible with LoRaWAN and Helium technology (a device for managing digital I/O and one for serial communication) were deployed. These devices, also referred to as "nodes," can be placed near physical assets to collect real-time information on the state of the assets.

In the absence of a real field, alarms that arrived at the device through digital signals, such as those generated by the operation of a magnetothermal protection, were simulated on the first device through a *breadboard* connected to the digital inputs of the IoT device, which provided the voltage level necessary to activate the simulated input.

On the second device, a Modbus RTU serial communication with a control PLC was simulated using an IoT device capable of operating as a Modbus RTU Master using a laptop connected via an RS485-USB interface converter. A simulator was installed on the computer to create a virtual Modbus RTU device configured as a "slave" to respond to requests from the IoT Master device. Through *RailChain*, the necessary end-to-end checks were performed to verify that the digital model created reflected the operational conditions created in the field, thus validating the implemented architecture.

The last field finding refers to the second case study, which involves the digitisation of a dynamic asset. This functionality is tested by installing a LoRaWAN GPS-001 device on a car, trying to go beyond the coverage area of the installed *Helium Hotspot*.

Having already tested the integration of NFT *HeliumAdapter* with NFT assets, we limited ourselves to verify the correct updating of latitude, longitude, and distance travelled information on the NFT *HeliumGPSAdapter* associated with the IoT GPS device. This was done by viewing the status of the NFT using the *Rarible Marketplace* Testnet. Also in this case, the result was positive and, upon detecting five positions on an urban route of about 25 Km, the dynamic NFT is correctly updated even when the car goes outside the operational limits of the *Helium Hotspot* we installed, correctly performing the hand-over with several other *Helium Hotspots* already present along the test route. Despite the *Helium* coverage not being optimal, it was still sufficient to ensure traceability throughout the route (Fig.4).

4. Discussion

Based on the application of the proposed solution to the identified case studies and the experimentation carried out,

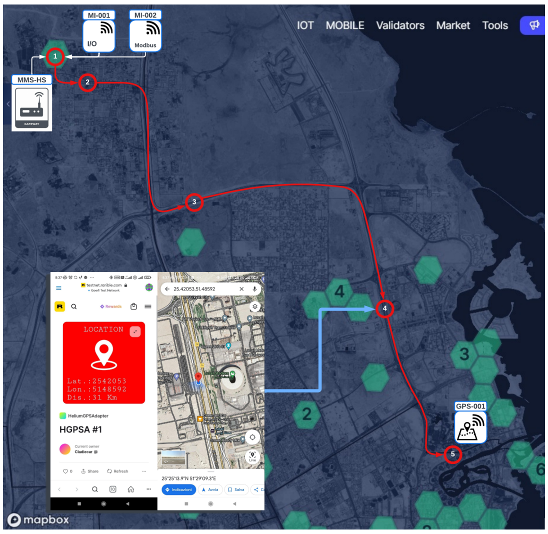

Figure 4: Test update NFT with GPS data

it can be asserted that the use of dynamic NFTs in the digitisation of railway assets can contribute to the improvement of the predefined areas:

Communication Infrastructure: Dynamic NFTs can be used to collect "live" data on the status of assets located in remote locations or on *Rolling stock* distributed over a wide geographical area. This was demonstrated through the implementation of the HeliumAdapter smart contracts and the ability to integrate NFTs minted by these contracts with any type of digitised asset. The adapters in question were developed by digitising the LoRaWAN devices connected to the Helium network, the same principle can also be applied to other technological solutions.

Management and Maintenance Systems: The proposed approach can support the decentralisation of maintenance management systems, reducing costs related to the purchase of licences and fees for maintenance services. The proposed solution was developed without using any traditional database but exclusively the Ethereum blockchain and the IPFS distributed file storage and transfer system. This does not mean that a similar system implemented in a practical application can completely eliminate the need for a local database, but it could significantly limit its size, resulting in a consequent reduction of costs.

Time to Market: The usability of services is improved by enhancing the efficiency and speed of information distribution. The NFTs minted according to the principles described represent a digital copy of the physical assets, making information immediately available to maintainers as soon as each individual asset is modelled. Conversely, traditional systems require a complex technological infrastructure, including servers, network storage, a database configured by specialized personnel, a centralised maintenance management system, and the collection of information across the entire railway network. The tuning of the system and the upload of all information onto the system takes a considerable amount of time and the system can only be used upon the completion of this process.

Documentation: Dynamic NFTs can provide a decentralised solution for maintenance teams to access technical documentation, configuration information, and software related to the assets to be maintained, thereby improving the efficiency and quality of maintenance activities. This is ensured by associating with the assets a QR code, the scanning of which will invoke an instance of *RailChain* that will return the associated information. The QR code will be printed on the identification label applied to the physical asset; by scanning the QR code with any mobile device, the information will be immediately available.

Event Logging: In our view, this represents the strength of the proposed solution, namely the integration of IoT and Blockchain technologies. IoT technology integrated with the digitisation of assets via dynamic NFTs allows for the indelible registration on the blockchain of the usage state and anomalies that have occurred to an asset throughout its lifecycle. This constitutes an incentive to carry out the necessary preventive and corrective maintenance cycles and to register them on the blockchain concurrently with the actions taken to demonstrate that the asset has been kept in optimal conditions. As a further reinforcement of the virtuous cycle, it is conceivable to incentivise maintenance workers to fulfil their duties by rewarding them with tokens for every correctly completed maintenance cycle.

It should be kept in mind that the application of the proposed solution in a real-world context entails considerable complexity and the need to overcome certain technological and regulatory challenges related to scalability, security, privacy, regulation, and interoperability.

The system's security is a critical aspect in the implementation of solutions based on dynamic NFTs and IoT technologies. It is vital to prevent possible external attacks that could compromise the security of digitised information and its integrity. To face these challenges, various countermeasures can be adopted, such as smart contract auditing to identify any vulnerabilities, increasing the number of nodes to ensure system redundancy, the use of authentication and authorisation protocols to limit access to sensitive information, and encrypting information to ensure its security in case of theft or loss.

To ensure maximum security, it is important to develop an integrated approach to security that includes constant risk assessment and the implementation of appropriate security measures to mitigate the identified risks.

Particular attention should be paid to the audit of smart contracts, an important security practice that involves the review and analysis of smart contracts to identify any vulnerabilities. To carry out an audit of smart contracts, an approach based on static and dynamic analysis techniques is required. Static analysis involves the review of the smart contract's source code to identify any vulnerabilities or errors in its implementation. Dynamic analysis involves simulating the behaviour of the smart contract to identify any vulnerabilities.

These analyses should be carried out using specialised audit services offered by third-party companies. These services involve the analysis of the smart contracts used for the digitalisation of assets and the generation of detailed reports on any vulnerabilities or problems encountered.

5. Conclusion

The proposed solution as a proof of concept responded optimally to the project objectives. Further steps for improvement are possible, for example, by utilising the NFT ERC-998 protocol [38]. The ERC-998 indeed allows for the possibility of composing tokens into lists or trees of ERC-721 and ERC-20 tokens connected by ownership relations. Each structure of this kind will have a single address at the root of the structure, which will also be the owner of the entire composition. The whole composition, or a branch of it, can be transferred with a single transaction by changing the owner of the root. This feature ensures the consistency of the asset link structure, mitigating the risk that a child asset's paternity link is changed without the transfer being recorded in the current parent asset's metadata.

Therefore, in a case of real implementation, the recommendation is certainly to implement the modelling using the ERC-998 protocol.

The study in question was based on a simplified model implemented using the ERC-721 protocol, elucidating the relationships between the assets within their metadata and assuming the following constraints:

- Any potential changes in the relationship between the assets are recorded manually, ensuring the metadata and related tokenURI are updated *On-chain*.
- All implemented NFTs belong to the same owner and are not partially transferred.

In our view, the primary limitation to the use of blockchain-based solutions remains the negative perception that many people have of this technology, often associated with financial speculation on digital assets and seen as unreliable and a potential source of scams. This negative perception hinders the adoption of this technology by many organisations, preventing the full exploitation of the potentialities of the blockchain, such as transparency, security, and decentralisation.

However, it should be noted that the spread of the application of the blockchain paradigm in asset tracking and railway maintenance does not necessarily have to occur with a *Top-down* approach, that is, starting from the need of a railway operator to implement an efficient maintenance management system for the entire transport network managed. We can also envisage a more gradual introduction approach of the *Bottom-up* type, starting from the product, where the component manufacturer used in the sector provides digisation of the marketed asset as an additional *plus*.

The use of NFTs in the railway maintenance context could be applied by Rolling stock manufacturers for public transport by implementing a digital ownership certificate for each asset, providing detailed information on manufacturing, certification, the PBS, spare parts, technical manuals, and preventive maintenance cycles to be performed. The operational manager of the infrastructure would thus be incentivised to use the same technology for managing the life cycle of the asset.

In conclusion, we can affirm that blockchain technology, enhanced by integration with IoT technology, has reached a degree of maturity such that its applications can be considered the new technological frontier. The blockchain paradigm is gradually overcoming the negative perception and prejudice to emerge as a reliable, secure, and decentralised solution for a wide range of applications in railway public transport, metro, and tram, surpassing traditional challenges related to data and process management.

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