Block-chain and Future Communication based Decentralised Train Control System

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Abstract-- **Railways is becoming more reliant on digital technology to achieve higher performance, safety and reliability. Adaptation to new drivers of the digital economy is visibly marked by emergence of the Industry 4.0 led by AI/ML and block-chain as well as focus on digitalisation efforts in Railways.**

Globally, Rail companies implemented a vast array of new services and applications using digital technologies, be it for providing more information and leisure services on board, improving the monitoring of the assets or automating operations. Changes introduced by digitalisation in railways are perceived by many stakeholders as an opportunity, owing to the benefits it can offer, but also as a challenge. Indeed, it requires a change of mindsets and innovative business models. Rail digitalisation also requires substantial capital investment and a strategy to tackle cyber threats. This paper brings out as how to handle such challenges by leveraging digital transformation to improve the safety, efficiency and competitiveness of the Railway sector.

Block-chain is a new technology with potential for acting as an enabler for data integration, trust and meting security challenges. It has many benefits and applications; some of these are reduction of cloud server maintenance costs, support of time critical applications, resilience and security, trust, scalability and decentralization. However, the technology needs to be further developed to overcome challenges such as scalability, security, anonymity and cost among others.

Keywords: Block-chain based rail control systems, Digital railway, Block-chain, Smart contract, Technology adoption rate, Slicing, Virtualisation, Digital twin

I. INTRODUCTION

CREATION of safer, faster, smarter, more environmentally and user friendly mobility systems constitutes human's transport vision [1]. One of the main components in the creation of the next generation of railway systems is the development of "the rail digital transformation". The main technologies and solutions that have been seen as an accelerator to the digital transformation include Internet of Things,Big Data Analytics, Cloud Computing, FRMCS (5G), and Automation and Robotics [1, 2]. Adoption of these technologies will meanransition to "Railway 4.0" or the "Digital Railway".

From conventional signaling systems to remote condition monitoring systems,Railway technologies have taken noteworthy steps towards automation and digitalization. To achieve higher performance, safety and reliability, the organisation is increasingly becoming dependant on digital technology. For this purpose, data is indispensable torealizedigital revolution [3]. Quite large amount of data is being collected by Railways around the world some of them are looking for better ways to utilize this data, by making sure it is integrated and can be availed by stakeholders in a productive manner that adds value. Since, data integration and knowledge mining is quite a challenge, organizations are looking for better ways for integrating data and obtaining more valuable knowledge out of it. Towards this objective, Block-chain offering security and decentralization benefits.promises to provide a new enabler for data integration forvarious stakeholders in railways and transportation industry.

Block-chain, a Distributed Ledger Technology has been identified as a key enabler for further automation and digitalization of the railways [1-3]. In these papers, authors mention some examples which utilized Block-chain within an IoT application, advantages that the block-chain provided to IoT and disadvantages or challenges that remain to be solved. This technology requires a high degree of cooperation from multi-actors [4] within different transport organizations which raise the questions related to the "when" and "how" to utilize the benefits of the block-chain within the railway context.

Author conducted a moderate literature review on the use of block-chain around different industries, in particular IoT applications, and in the railway context, gathered evidences on opportunities and challenges that the block-chain technology can offer. The paper looks at different railway applications that are already experimenting with the block-chain or might have the potential for its utilization. Finally, the paper brings out benefits that have been gained from the usage of block-chain and the challenges that remain to be solved.

II. BLOCKCHAIN AND SMART CONTRACT

The block-chains are a group of distributed and decentralized data records interlinked through a cryptology process, called hashing. Data transactions happen among these blocks with a unique hash value, identified uniquely via a public key [5, 6]. While, each transaction is verifiable by other blocks using public key, a valid hash-key is essential to form a new block. A process called consensus is used to generate new blocks by a competitive process in the network. Different consensus mechanisms generate a new block in the chain. Consensus mechanism used by the most popular crypto-¬currency network is termed "Proof of Work". Other consensus mechanisms alsoexist, such as "Proof of Authority", "Proof of Stake" and "Proof of Elapsed Time".

Transactions happen in block-chain, on a peer-to-peer basis without a central authority, or amiddle man.Eachtransactionis verified by other blocks in a given network and recorded in every Node. This feature provides trust,security, transparency, and traceability -- the characteristc benefits ofblock-chain. Other benefits include enhanced efficiency, speed and cost reductions. Nevertheless, some benefits may not be achieved in an early stage [7].

Interesting feature, 'Smart Contracts' are block-chain applications used to transact data across the chains, also called 'Decentralized Applications' (DApps). They enable interface with block-chain users on the type of data which is being transferred across the network. Such applications execute themselves based on predefined attributes and conditions. In context of railways, one would expect various condition-monitoring sensors to be the blocks of the block-chain, whereasa preventive executable maintenance software is the Smart Contract. Another example: track circuits, axle counters, trackside signals and machines and trains (rolling stocks) to be stringed as blocks of the network whereas the Decentralized Application or the Smart Contract be the scheduling programand control code [5 -8].

III. BLOCKCHAIN IN RAILWAYS

One of the key dimensions in the future development of higher levels of automation in railway systems is through the use of IoT applications [1-3]. This can be seen through development of the next generation of control and monitoring systems. IoT applications have been rapidly increasing in many sectors across the globe, from ocean to space. The IoT application will consist of a group of layers: a presentation layer, a network layer and an application layer. Use of block-chain within these layers promises very high level of security, decentralization and automation.

Interestingly, Block-chains have been used as decentralized system of cooperation among smart objects [8]. However, current IoTsubsystems are cloud-based computing infrastructure thathas disadvantages including difficulty of supporting time-critical IoT applications, security and trust related issues and high cloud-server maintenance costs [8, 10]. Block-chain helps in overcoming these challenges; however, actual experiments and prototypes are still being developed around the world. Some potential block-chain applications across different industries including Railways are in Table 1.

TABLE 1-- POTENTIAL AREAS OF APPLICATION FOR BLOCKCHAIN [8-17]

	General
i.	Data storage management, the block-chain can be used to store access control data as data storage systems in a multi-tier IoT architecture
ii.	Trade of goods and data, identity management
iii.	Rating system
iv.	Manage firmware updates for IoT devices
v.	Demand manufacturing
vi.	Smart diagnostics and machine maintenance & Traceability
vii.	Supply chain tracking
viii.	Product certification
ix.	Consumer to machine and machine to machine transaction
x.	Tracking supplier's identity and registry of assets and inventory
	Railways Use Cases
i.	Mapping and Managing of complete Supply Chain
ii.	Automation of internal accounting process
iii.	Conducting and automating contracts between machines and objects
iv.	Block-chain with IoT to manage signalling, passenger information systems, ticketing and goods delivery

IV. BLOCKCHAIN FOR RAILWAY APPLICATIONS

Blockchain as an enabler for Remote Condition Monitoring with data utilization: Remote condition monitoring is a commonly used concept in the railway industry, to know the status of physical and operational conditions of different railway system assets (track, trains, switches, point machines .and so on) to be being monitored through a network of sensors providing data on malfunctioning, or need for an effective maintenance required for a particular asset. This paved the way for further automation in operations and maintenance in railway systems.

Utilization of sensor-data by different stake holders in railway industry and the actual cost/benefit analysis has proposed a challenge for the industry.

To realize better utilization of data among stakeholders, a number of enablers need to be implemented, like enterprise software bus (EBS), ontologies, linked open data and the block-chain. Block-chain imparts quite a number of benefits to the railway industry, like added security of IoT nodes and integration of data as well as utilization through a micropayment scheme. However, there are challenges including illegal content distribution across the block-chain that might include "innocent nodes" as all transactions which happened in the block-chain will simultaneously be recorded in all blocks.

Thoughtechnologyis yet to reach the maturity required for mainstream adoption, yet it is the opportune time for building prototypes and experimentation [4].

Railway Organizations experimenting with block-chain: Several organizations are experimenting with block-chain technology for a number of applications inrail industry. For example, DB Systel is working on the digitalization of the railway industry and achievedmapping a complete supply chain, resulting in automation of internal accounting process and conducting contracts between machines and objects. Likewise, over a nine-month period, Russian Railways (RZD) successfully carried over 5000 freight consignments via an electronic trading platform powered by Block-chain technology. The State Railway of Thailand (SRT) is investing in block-chain technology with IoT to manage signalling, passenger informationsystems, ticketing and goods delivery [19, 20].

V. BLOCKCHAIN: CHALLENGES AND OPPORTUNITIES

Opportunities that block-chain offers for IoT applications in Railways include reduction of cloud server maintenance costs, support of time-critical applications, resilience and security, trust, scalability and decentralization [6, 8]. There are still a number of challenges that is facing the block-chain usage in IoT applications and in the railway industry in particular, these challenges include cost, scalability, anonymity, integrity, efficiency, privacy, regulation, awareness, smart-contract vulnerabilities, building trust, gaining full participation of all stakeholders and data standardization [Table 2].

TABLE 2 -- A LIST OF OPPORTUNITIES AND CHALLENGES OF BLOCK-CHAIN IN IOT

Block-chain Benefits
• Greater level of security. • Transparency • Traceability. • Increasing efficiency and speed • Cost reductions.
Potential Block-chain Promising Benefits to IoT Applications
• Higher level of decentralization. • Higher levels of security and trust. • Higher levels of support to time critical IoT applications. • Reduction of cloud server maintenance costs.
Potential Area of Concern for the Usage of Block-chain within IoT applications
Scalability
• Large number of transactions generated by sensors data becomes expensive to store on the block-chain. • A low throughput transactions
Security
• Most secure approach if develop IoT applications can happen is of top of an already existing stable block-chain, this block-chain should have a great number of honest miners who can ensure integrity. • the distribution of illegal content across the block-chain which might include "innocent nodes" as all the transactions that happened in the block-chain will be recorded in all the blocks
Anonymity
• There is a possibility of linking IoT devices to their owners, thus future solutions on this issue has to be developed.
Costs
• Storing sensors data on the Block-chain might become expensive and impractical

For the rail and logistics world to successfully realise the prospective benefits of the block-chain offer, Four preconditions must be met: building Trust, gaining the full participation of all stakeholders, overcoming technical challenges and data standardisation.

VI. DECENTRALISATION OF TRAIN CONTROL -- ARCHITECTURE AND TECHNOLOGIES

Conventional train control systems are normally centralized in two ways: technically and logically. Logically, there is onlyone business entity, namely the 'infrastructure operator' operating the control system.This is the only party with full access rights. It may or may not permit 'read-only' access for train operators at its own volition. Technically, the control system is normally centralized as cost issues don't entail a multi-location/ multi-node set-up. Moreover, a "hot standby" or even "active-active" set-up implies data be replicated completely before it can be considered as "written through"; which may enhance latency besides putting strain ondata links between locations.

Proposed architecture (Fig.1) is primarily based on technical decentralization, *i.e.* on multiple nodes.

Block-chain identity of the train is the actor which orders paths (*i.e.* performs reservations of an infrastructure element for a given timeframe); it interacts with the block-chain identity of the infrastructure element via the Smart Contract which is the Gatekeeper (ensuring consistency and a safe global state). The Smart Contract is the entity which changes the "should be" part of global state.

When it comes to logical decentralization, the situation is more intricate. Logical decentralization means that the nodes belong to multiple parties. This immediately poses the questions of authority, agreements, responsibility, and liability. When it comes to safety and human life, strong authorities are the traditional choice. Implicitly, a single authority means a single (central) responsibility. In aviation sector, the pilot and the

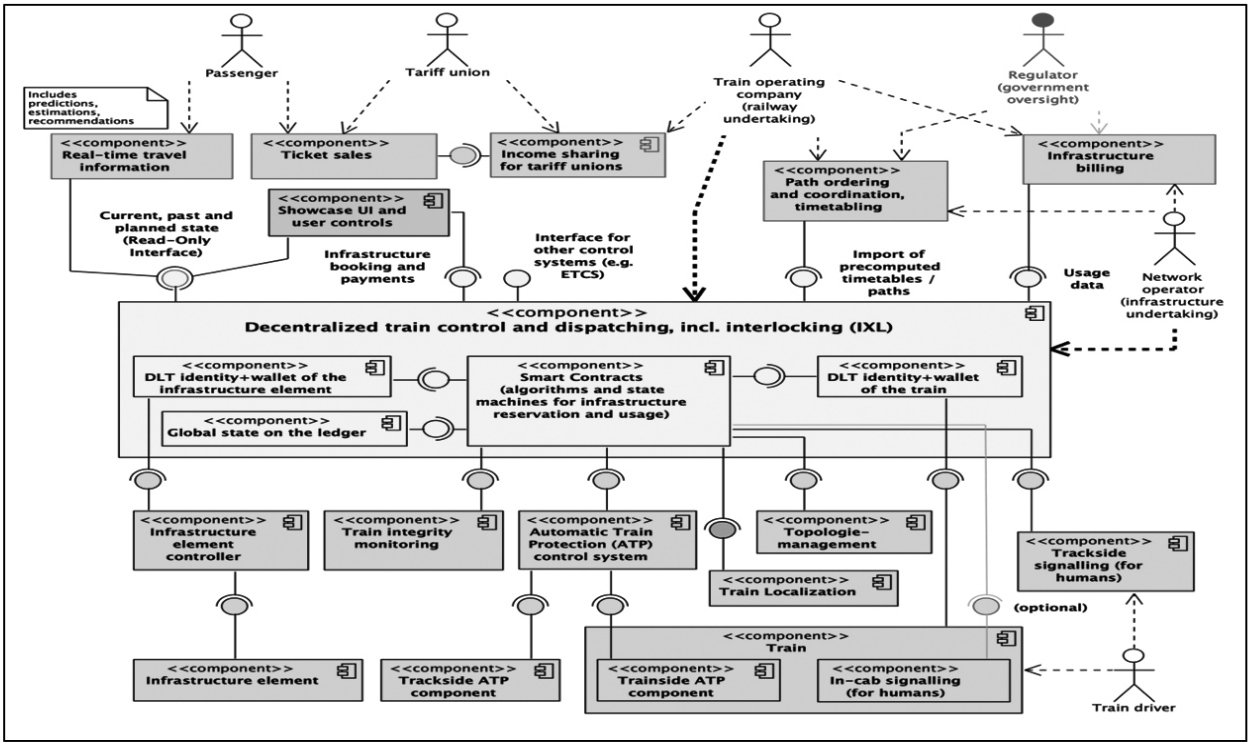

Figure 1 Case study architecture (partially implemented by the prototype) [24].

co-pilot are the example where strict rules of authority in a multi-party set-up are used to prevent a stalemate, as there is no arbiter to act as an intermediary between the parties.

Logical decentralization is inherently more complex than logical centralization, as it needs to address the situation with failing/unreachable nodes, the meaning of dissenting minorities, party splitting and unstable behaviour (cf. the "Byzantine Generals" problem and the associated body of research).

Ultimately, the distributed ledger based solution architecture is technically suitable for both logically-centralized and logically-decentralized set-ups: since the solution used a private-consortia (non-public) Block-chain as the "engine" to run algorithms and store data, additional nodes can be added, and additional parties can be on-boarded.

It is important to stress that reservations (and payments) are handled in a peer-to-peer fashion between trains and infrastructure elements (such as switches); the IoT (Digital) Twin of the infrastructure element is in control of the element's block-chain wallet. A block-chain, on the other side, is the event bus and the recording ledger, but it is not a first-level, self-aware, individually-acting entity with own interest. At the same time, the participants of the block-chain network safeguard the outcome of the peer-to-peer transactions, because these transactions (*e.g.* admitting a train into a track section) are safety-relevant and affect all peers—not just two.

Distributed Data Ledger Platform (DDLP) based on Block-chain: Figure 2 depicts a general data platform wherein various use cases of Block-chain in railways can be simulated and created using Digital Twin prototype methodology.

VII. BLOCKCHAIN BASED RAIL CONTROL SYSTEM

Railway operations have a complex framework of rules and regulations, with powerful and complex and centralised systems in place to control trains, personnel and infrastructure elements. These systems have reached a very high pedigree, but their cost and complexity impact competitiveness and operational stability of railways, at a time where zero-emission vehicles, self-driving algorithms, ride-sharing/car-sharing and changing travel patterns increase the pressure to become more cost-effective. The adoption of cutting-edge technologies such as ETCS [25] and ERTMS [26] is progressing slowly.

The Block-chain-based Railway Control System (BRCS) [27] is an approach which pursuits the vision of automating traffic management and (re-)dispatching, building on software-defined safety mechanisms, decentralised train control, interlocking and train protection. Innovative technologies such as AI and 5G (FRMCS) can be used to support the implementation.

In a *first* realization phase, BRCS seeks to satisfy the secondary lines' needs by providing a streamlined "safety core" for the *minimum* needs of train operations: train collision avoidance,

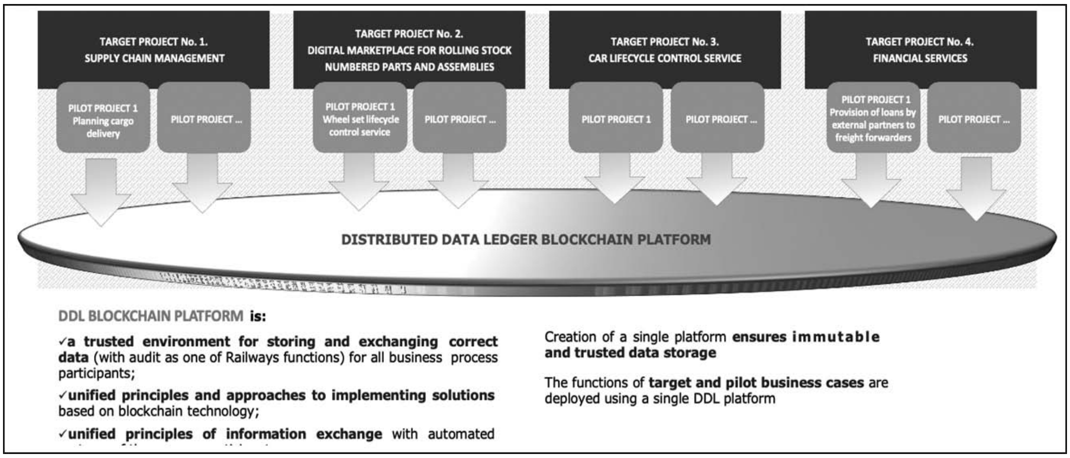

Figure 2. Distributed Data Ledger Platform (DDLP) based on Block-chain.

interlocking control, signal control, inter-facing automated Train Protection (ATP) such as PZB etc. At the same time, the BRCS approach addresses operational efficiency by leveraging the traffic management aspects.

BRCS relies on a distributed and replicated software solution for the interlocking core, which can also run in a cloud environment – so that expensive proprietary hardware is no longer needed. In order to efficiently build the BRCS implementation with features such as tamper-proof-ness, resilience, high availability and self-healing, BRCS relies on the proven and high-performance Block-chain technology.

Usage of block-chain for BRCS means that:

1. Decisions and underlying logic are stored in a tamper-proof manner; Consensus approvals are stored on the ledger and cryptographically secured.
2. The block-chain network is managed jointly and transparently and the safety-relevant control logic can only be updated according to consensus (for example, the EBA or any other mandated authority can participate in the network as a supervisor).
3. Each of the Block-chain nodes has the same authoritative "truth": interlocking failures are thus much less likely.

In addition, BRCS has the following unique selling points:

a. All information (timetables, route bookings, ongoing journeys) can be seen in one system which unifies all the aspects.
b. The BRCS implementation can be used directly for billing (routes, station stops), especially for pay-as-you-go scenarios [29].
c. The driver can directly see the complete situation on the route network without having to contact the control centre (via phone or radio): the person in the driver's cab is no longer in a "blind flight".
d. BRCS is designed for achieving better safety on routes without ATP or even without signalling, by using software-side warning mechanisms and additional localization technologies (GPS/GNSS) as an addition to human communication.
e. The BRCS architecture is geared towards independent route booking by vehicles ("headless operations") and offers interfaces for external or manual traffic optimization and scheduling, *e.g.* using AI (machine learning) or by human dispatchers.

A generic runtime architecture with layered approach is depicted in Fig.3, where middle layers indicate elements and implementation of block-chain digital assets/product, over existing hardware and network infrastructure.

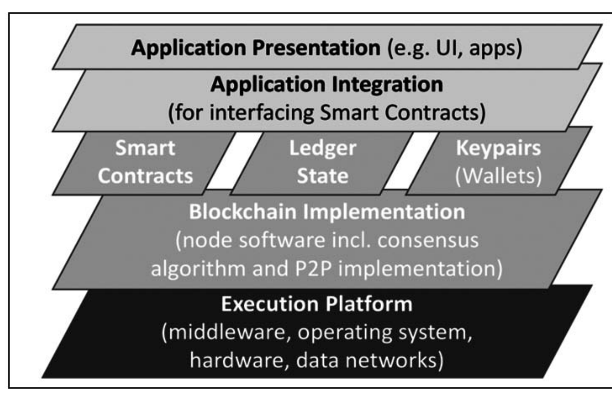

Figure 3. Layers of a block-chain application.

BRCS will contain both externally-sourced layers and project-created layers. Inconsistencies in complex, layered and componentized applications can be prevented using systematic configuration management and acceptance testing (even for "standard", externally-sourced COTS dependencies). To save time and space, updates are often designed to be incremental or differential - at the expense of having to ensure that such updates are applied in correct order, atomically and in a durable way.

VIII. BLOCKCHAIN AND COMMUNICATION BASED TRAIN CONTROL (CBTC) SIGNALLING SYSTEMS

In existing Communication Based Train Control (CBTC) system, there are many information security threats especially in train-ground communication, so information security protection methods of CBTC system are required to be cyber-secured. For need of increasing information security, block-chain technology is used to train-ground communication of CBTC system. Based on block-chain technology, CBTC system information security testing environment is set up. Testing results demonstrate that the train-ground communication information security of CBTC system based on block-chain overcomes the single-point failure of centralization key management and doesn't influence the run time of CBTC system.

Additionally, new generation of railway mobile communication, Future Railway Mobile Communication System (FRMCS), envisioned by ETSI and UIC based on principles of 5G of 3GPP and IMT-2020 of ITU *viz.* Virtualisation, Slicing and Layering as well as Securing also adds to security of communication in addition to enhanced throughput, reduced latency, high connection density and availability. Main attribute of FRMCS is separation of Application and Service Layers from underlying Infrastructure (Transport) layer which adds to flexibility and efficiency and ease of use.

The CBTC system consist of these subsystems [4] as shown in Figure 4.

The main subsystems are CBTC Wayside equipment, CBTC Train-Borne equipment, CBTC Data Communications equipment. In addition, all CBTC systems contain ATP (Automatic Train Protection) systems and ATS (Automatic Train Supervision) equipment. Also, some CBTC systems may also contain ATO (Automatic Train Operation) and ATC (Automatic Train Control) systems [29].

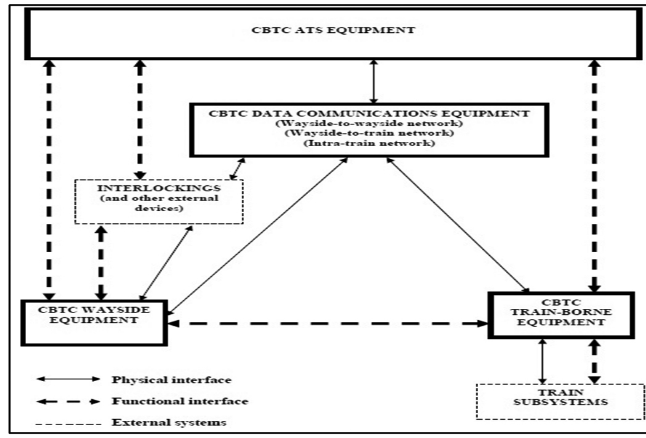

Figure 4. CBTC Subsystems.

CBTC Wayside equipment consists of Balises and Interlockings. ATS-ATP or ATO control centres are other CTBC wayside equipment. A computer on the train that manages the authority to move the train using driver, train and other communication modules are CBTC train-borne equipment. Radio communication system is a combination of software and hardware equipment, which are data communication computer, antenna, Wi-Fi control centre and these are responsible for radio communication between the train and wayside [30]. The important CBTC system equipment are shown in Figure 5.

Working Mechanism of CBTC Signalling Systems: The CBTC system relies on two-way continuous digital communication between each controlled train and control centres along the railway. On a railway equipped with a mobile block system, the line is usually divided into areas or zones as shown in Figure 6. Each zone is under computer control and each has its own radio transmission system. Each train transmits its identity, location, direction and speed to the regional computer that makes the necessary calculations for safe trains and sends these calculations to the next train. The radio link between each train

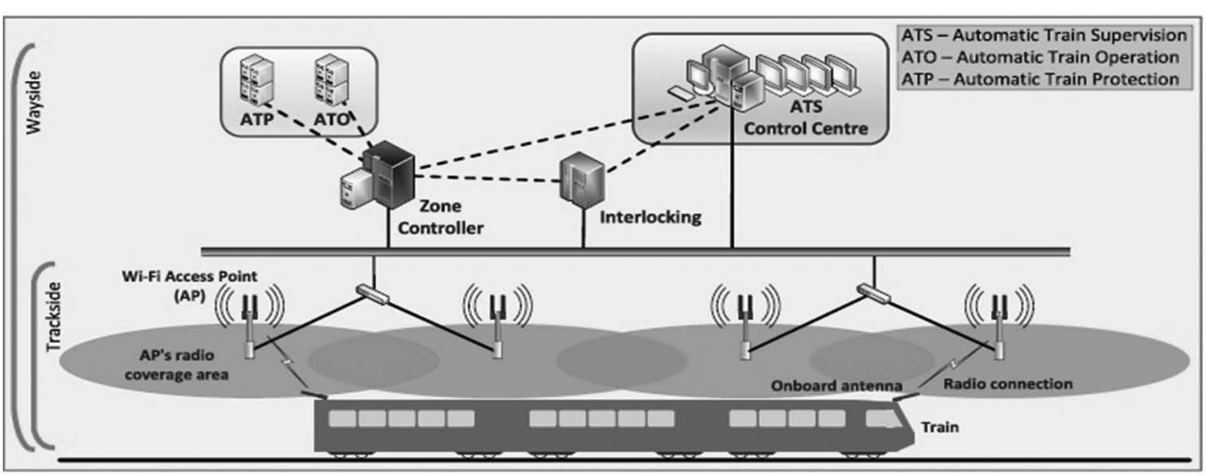

Figure 5. CBTC equipment [32].

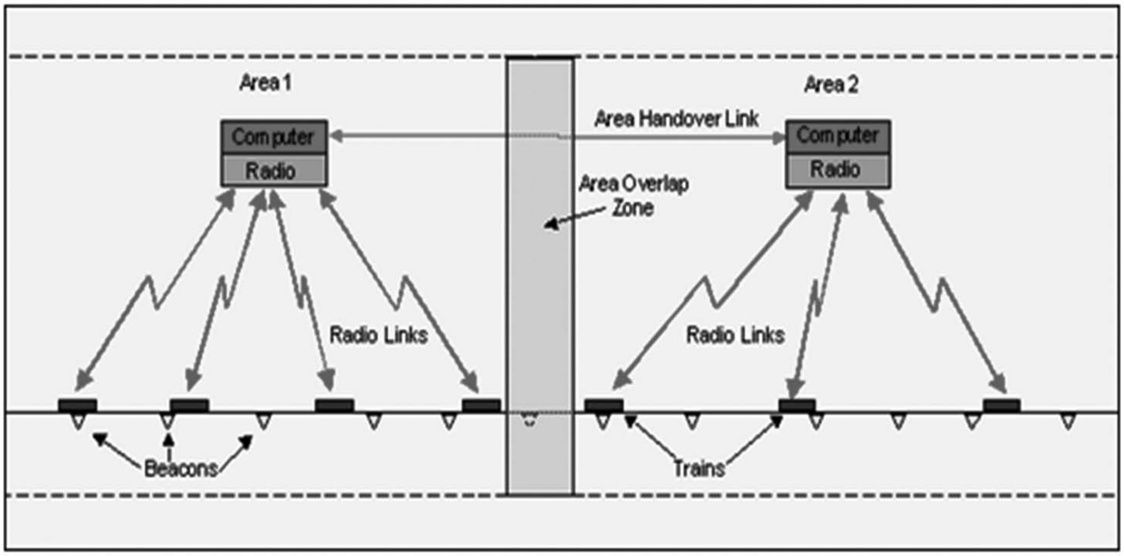

Figure 6. CBTC system.

and zone computer is continuous; at which point the computer knows the location of all the trains in its territory at any given moment. These radio links transmit each train the position of the train in front of it and give it a curve to stop before reaching the train on the front. If the train does not follow the commands, the ATP or ATS system stops the train automatically.

Using the information, about the route status and the type of the route set, state of the elements on the route and the train location information already determined from the message received from the trains, CBTC system will determine the movement authorities as shown in Figure 7.
CBTC system sends movement authority message to each train and this message contains some important information as following:

- Gradient profile
- Static speed profile
- ATP door enabling information
- ATO platform data and stopping point information
- Reversing area information
- Temporary speed restrictions
- EoA: End of Authority is the location to which the train is authorized to move.
- DP: Danger Point is the location that can be reached by the front end of the train without a risk for a hazardous situation.
- The end of an overlap is a location beyond the danger point that can be reached by the front end of the train without a risk for a hazardous situation.

IX. CONCLUSION

Railways around the world are moving towards digitalization to enhance their operations. Block-chain is a new technology with potential for acting as an enabler for the data integration,

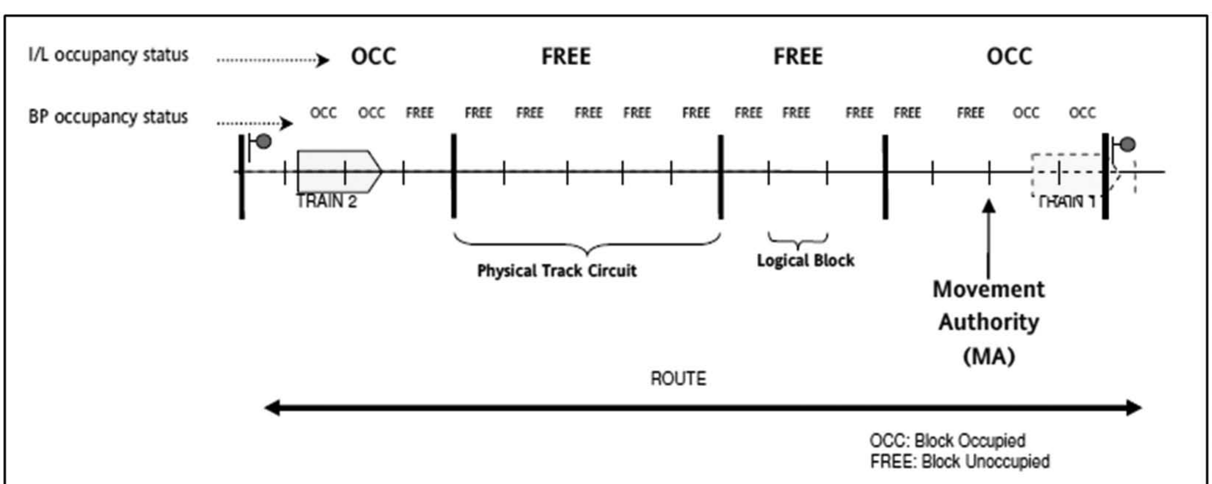

Figure 7. Movement authority in CBTC system.

trust and meting security challenges. It features benefits such as reduction of cloud-server maintenance costs, support of time-critical applications, resilience and security, trust, scalability and decentralization. However, the technology needs to be further developed to overcome challenges such as scalability, security, anonymity and cost among others.

In this paper, a moderate literature review of some of block-chain applications in the field of IoT has been demonstrated, in particular, the use of block-chain in different industries. In addition, next generation version of Railways mobile communication, FRMCS envisioned by ETSI and IUC (based on 5G features of All-IP, Virtualisation, Slicing, MOCN, MORAN, Layered approach and Security) is advocated to be used for communication purpose. In addition to looking at various railway block-chain related current and potential applications, a simple analysis of the technology potential adoption rate has also been discussed. It was found that the Block-chain can offer a number of benefits including added Security, Trust and Decentralization for several railway applications, starting with Decentralised Train Control.

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He is Vice-President and Trustee of PTCIF and Chairs BIF committee on Rural Digital Infrastructure. He founded NGN Forum in India to spread awareness and capacity building in the field of emerging technologies. As a member of Expert panel of Commonwealth Telecom Organisation, he conducts training programs in the areas of NGN technologies, broadband policy and regulation, interconnection costing in NGN era, spectrum management, IPV6, Digital transformation, blockchain and blue-ocean strategy. He is first Indian recipient of IPv6 Hall of Fame Award – 2019 by Global IPv6 Forum and also the Chairman of Bharat IPv6 Forum.

Presently, he is working as Chairman, BLUETOWN, India & BIMSTEC, S. Asia to forge newer partnerships and "Making It Happen" the Vision of "Connecting the Unconnected people living in Rural areas of World".