Towards Intelligent Train Control Systems

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Abstract—**Future train control systems are expected to support high speed railways, to be automated and intelligent. European Railway Traffic Management System (ERTSM) and European Train Control Systems (ETCS) provide a standard aimed at optimization of driving, constant control on the effect of actions taken for train safety and activating of train braking in case of emergency. Radio Block Center (RBC) is a central control in the ETCS ground topology and is responsible for the security of each train in its area. Currently, the RBC is proprietary equipment with monolithic design. In this paper, we propose a new disaggregated open architecture of RBC which enables embedding intelligence. The proposed architecture of intelligent RBC is based on separation of nonreal time functions and near real time functions. A use case illustrates the approach applicability. Some implementation issues are discussed.**

I. INTRODUCTION

Railway systems need to provide safe, secure, reliable, resilient, and time-determined services. Safety guarantees lack of catastrophic consequences for the passengers, drivers, and the environment. Security ensures prevention from intrusions and an unauthorized information disclosure. Reliability ensures the correct service continuity while the resilience is related to ability to resist failures. Provisioning of low latency time-synchronized services is regarded as time determinism.

The constant evolution of railway control systems is toward automation of railway operations. Enablers of railway control system automation are new technologies for improving security, for connecting on-board and infrastructure objects to collect information from sensors to guide the correct railway operations and to anticipate potential failures, and for creation of user-centric services. Exponential technologies that help to increase the efficiency of railway operation control systems include mobile communication technologies, Internet of Things (IoT), big data analytics, artificial intelligence (AI), cloud computing, and cybernetics [1], [2], [3].

European Rail Traffic Management System (ERTMS) is standard programme for "European signaling and speed control system that ensures interoperability of the national railway systems, reducing the purchasing and maintenance costs of the signaling systems as well as increasing the speed of trains, the capacity of infrastructure and the level of safety in rail transport" [4], [5]. The programme is aimed at improvement and development of reliable and safety railway transport services, and at transition to open and competitive market of railway construction and systems [6]. The main advantages of ERTMS include the following parameters: safety, cost, accessibility, interoperability, and maintenance. It comprises European Train Control System (ETCS) and GSM-R which will be gradually replaced by Future Rail Mobile Communication System (FRMCS).

ETCS is the standardized, interoperable Automatic Train Protection / Automatic Train Control system used in Europe. The introduction of ETCS is realized in four functional levels (from 0 to 3), which depend on the installed railroad equipment and the way the information is transmitted to the train [7], [8]. For safety movement the ETCS trains need to know their current position, the maximum allowed speed in the track section and the next safe allowable position. Eurobalises mounted on the tracks provide the rough train current position and the onboard train system estimates the fine train position using e. g. odometers. ETCS level 2 and 3 provide bidirectional communication between the terrain and Radio Block Center (RBC) which is the heart of the trackside system. Currently, RBC is monolithic equipment responsible for the management of the data exchange required for safe train travel [9].

FRMCS is a global standard for railway communications which enables improvement of safety and operational efficiency and fosters development of innovative passenger services [10], [11]. With minimized network latency and the usage of cloud technologies, FRMCS enables automatic train operation, remote control and IoT [12], [13], [14].

The future evolution of ETCS and the deployment of FRMCS can be supported by using AI and edge cloud technologies. AI in conjunction with jointly massive data collection, data mining and intelligent algorithms may improve safety, security, autonomous train driving and mobility [15], [16]. Edge cloud enables data processing and storage at the edge of the network and may contribute to delivering high transmission rates, high availability, and low latency [17], [18], [19], [20].

In this paper, we propose a disaggregated architecture of RBC based on the core pillars of openness and intelligence. Openness aims eliminate proprietary and vendor specific hardware and software realization by defining open interfaces, virtualization of network functions and cloudification. Intelligence is necessary because of the complex, multi-dimensional data-based decisions which must be reasoned in nonreal time and near real time. The research is inspired by the approach applied in the Open Radio Access Network (O-RAN) concept [21].

The paper is structured as follows. Next section provides a brief description ETCS levels and focuses on the RBC functions, interfaces, and standardization. Section III introduces the concept of FRMCS which enables embedding intelligence. Section IV discusses the main railway application area where AI and machine learning (ML) algorithms may be used. Section V presents the proposed disaggregated architecture of intelligent RBC and illustrates the RBC disaggregated functionality by a use case. Section VI discusses some implementation issues. Finally, Section VII concludes the paper and describes in brief the future work.

II. ETCS Automatic Train Control

ETCS as a part of ERTMS defines levels of signaling between train and track. ETCS levels are related to how the railway system can operate depending on the installed trackside equipment, on communication between the trackside equipment and the onboard system, and on distribution of on-board and trackside functions [22], [23].

ETCS Level 0 is applied when the train is equipped with ETCS functionality, but the trackside is not equipped with any train control system. The onboard control system monitors only the train maximum speed.

ETCS Level 1 is applied when the train is equipped with ETCS functionality operating on a line equipped with Eurobalises. The Eurobalises pick up trackside signals and transmit them to the Movement Authority, which is responsible for permission to cross block sections, along with route date at fixed points. Using this date, the on-board control system continuously monitors and calculates the braking curve and the maximum train speed.

ETCS Level 2 is radio-based signaling and train protection system. It is applied when the train is equipped with ETCS functionality operating on a line controlled by an RBC and equipped with Eurobalises and Euroradio. The RBC continuously transmit to every train the speed and the distance between trans to be observed depending on the position each train on the line, on the track constraints or any other temporary circumstances. The RBC receives automatic reports from the trains about their exact position and travel direction at regular periods and sends Movement Authorities to the onboard control system to allow the train to move itself on the track. The train integrity supervision remains at the trackside with track release devices. The Eurobalises are used at Level 2 as passive positioning beacons, and the train determines its position between two positioning beacons via sensors. The onboard control system monitors the maximum allowed speed.

ETCS Level 3 is like Level 2 with full radio-based control on the train speed and without the need of track-release signaling devices. The RBC functionality is integrated with interlocking functions. The train position is calculated on actual distance between a train and the next one. Movement Authorities are provided on train positioning information. The onboard control system is responsible for train integrity at very highest degree of reliability.

The RBC is a computer-based component of the ETCS Level 2 and Level 3. It is responsible for guidance and monitoring of trains in its area. It receives information from external trackside systems (such as interlocking, route occupancy, route state) and from onboard systems for trains' positions, generates Movement Authorities and sends them to the trains. The process of exchange of train information between two RBC when the train overpasses an RBC area is called handover. The RBC functions are not specified in detail. Common RBC functions include the following:

- Generation of movement authorities
- Receiving positioning information about trains in its RBC area
- Handover of a train to a neighboring RBC area
- Operating in different ETCS modes, e. g. full supervision, on sight, staff responsible, shunting or reversing
- Provision of concatenation information
- Announcing a radio hole
- Evaluation of potentially dangerous situations and commanding emergency stops
- First route assignment to a train
- Train chasing
- Acquisition of diagnostic information
- Setting up temporary speed limits
- Joining and splitting trains
- Sending the national values to the train
- Monitoring of the radio link
- Defining the safety reactions in the event of certain incorrect situations on the train.

While the user interfaces of the RBC are not standardized and are national specific, the radio interface to the train and the interfaces between trains are standardized.

The RBC operation enables maintenance access and dispatcher control. The maintenance access provides access to log files, storage and retrieval of messaging for malfunctions, RBC software configurations, updates and restart. The dispatcher control enables input of temporary data such as speed restrictions, changing of ETCS modes, emergency breaking etc. The RBC operation may be partially or fully automated, which may depend on existing trackside infrastructure. The trend is towards fully automated operation which makes intelligent decisions. The proposed disaggregated architecture of RBC, described in Section IV, defines two logical functions related to nonreal time and near real time functionality of the RBC, which are involved in nonreal time control loops and near real time control loops. The proposed logical functions can use data analytics and AI/ML training and inference to determine railway operation optimization.

III. FRMCS Service Architecture

Currently, most railway deployments use GSM-R network for communication between the RBC and trains. As it has been pointed out earlier, FRMCS is the successor of GSM-R. FRMCS can be based on fifth generation mobile communications (5G) which have the potential to support massive machine-type communications, to provide high-speed connections with low latency and ultra-high reliability. FRMCS will use cloud technologies to automate the train operation and to face the complexity of communication needs in railway environment [24]. The FRMCS standards define just the FRMCS architecture and user requirements based on analysis if different railway use cases.

The logical FRMCS architecture is described as logical function blocks and reference points between them [25]. The FRMCS design applies a separation between Railway Application Stratum, Service Stratum and Transport Stratum. The Railway Application Stratum provides railway-specific applications that use the services offered by the Service Stratum. The communication services in the Service Stratum provide means for communication exchange between applications and guarantee interoperable service behavior. The Service Stratum also provides complementary services used for ancillary functions such as provisioning of location information. The Transport Stratum provides a set of access and core functions for the FRMCS. The FRMCS has to be installed at the onboard/handheld side and at the infrastructure side.

The main logical entities in FRMCS are FRMCS Mobile Application Client, FRMCS Service Client, FRMCS Mobile Gateway, FRMCS Service Server, mobile radio, and Trackside Transport. The FRMCS Mobile Application Client enables application authorization to the FRMCS gateway. The FRMCS Service Client enables applications to use communication and/or complementary services. FRMCS Mobile Gateway enables humans or machines using FRMCS services to access the FRMCS Transport Stratum through FRMCS Service Clients. The FRMCS Service Server as a part of the Service Stratum provides endpoint functionality for service level sessions with FRMCS Service Clients and provides transmission of user profiles, authorization, location management, control, etc. The mobile radio is a user equipment which supports selected radio access (cellular, wireless, satellite). The Trackside Transport covers radio and core network functionality.

Both onboard/handheld side and infrastructure site host railway applications, FRMCS Mobile Application Clients and FRMCS Service Clients. Mobile radios and FRMCS are at the onboard/handheld side, while the Trackside Transport including trackside radio and the core network are at the infrastructure site.

IV. ARTIFICIAL INTELLIGENT TECHNIQUES IN RAILWAYS

Adoption of AI technologies in rail industry can drive the railways efficiency, reduce costs, and improve productivity. ML, as a subset of AI, is a technique by which a computer can "learn" from data based on training a model from datasets. There exist different ML approaches such as supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning [26]. Traditional ML techniques utilize various algorithm learning types to model functions and provide predictions from data. The Deep Learning technique which attempts to mimic the human brain makes ML much more powerful. It is essentially a multi-layered neural network which simulates the behavior of human brain.

In [27], the International Union of Railways describes the state of play of the European railway sector and perspectives, stressing on predictive maintenance. AI technologies which are currently being deployed within the railways include image recognition in the fight against terrorism, sales prediction through ML, chatbots and virtual assistance for passengers, robotics in trains, in railway stations and in warehouses.

Different maintenance types exist. The breakdown maintenance, or so called corrective maintenance, requires actions to be taken after a machine has failed. It includes troubleshooting to localize the fault and to correct it. The preventive maintenance comprises measurement and supervision, where many measurements are made with a view to prevent incidents or to find hidden malfunctioning. Condition-based maintenance is a preventive approach performed as driven by condition monitoring. Predictive monitoring can improve railway reliability, availability, safety, and punctuality, optimizing efficiency. The usage of AI for preventive maintenance in railways may pave the way for innovations.

As to [27], the predictive maintenance in conjunction with AI may be used for rolling stock and railway infrastructure. Some initial use cases include anomaly recognition of train bearing temperature, detection of wheel tread defects, protection against unintended threats (safety) and intended threats (security) during railway operation, etc. The usage of AI in preventive maintenance of infrastructure is an important issue because the train safety and integrity depend on the reliability and availability of tracks, bridges, tunnels, excavations and embarkments, etc.

In addition to the listed application areas above, AI/ML techniques may be used for autonomous train driving and train control, transferring the responsibilities from manual operators to onboard control system, for traffic planning and management, for passenger mobility and for transport policy [26].

Some of the measures that can be taken in preventive maintenance as well as some actions related to train control based on AI/ML models need to be implemented in real time, while other are nonreal time. Based on this separation, the proposed RBC architecture separates the nonreal time control functions from near real time control functions. A more detailed description of the disaggregated RBC architecture is given in the next section.

V. DISAGGREGATED ARCHITECTURE OF INTELLIGENT RBC

Fig.1 provides a high level view of the proposed intelligent RBC architecture.

All RBC functions may be virtualized that is they may run as containers above Railway Mobile Edge Cloud (RMEC). Management and Orchestration (MO) is responsible for railway management in the RBC area, optimization of Nonreal time Radio Control Unit (RCU), and for management and orchestration of the Railway Mobile Edge Cloud.

Railway Mobile Edge Cloud (RMEC) is a cloud computing platform providing virtualized infrastructure that is able to meet the requirements to host the relevant virtualized RBC functions (such as near real time RCU, Onboard train control system, Eurobalise, Euroloop, Interlocking, Control center). It can be based on Multi-access Edge Computing (MEC) technology [3], [19].

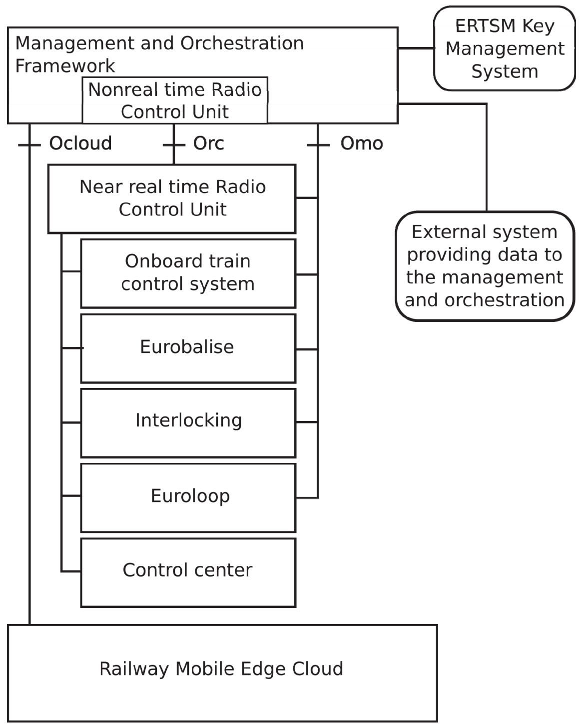

Fig.1 High level architecture of intelligent RBC

Nonreal time RCU is a logical function within MO that drives the content carried across the Orc interface. It hosts nonreal time applications, provides functionality to expose MO service to these applications, and environment for running AI/ML models including model learning, inference, and update for applications. The applications in the nonreal time RC enable nonreal time control and optimization of onboard train control functions and track control functions, and policy-based guidance to the applications in Near real time RCU.

Near real time RCU is a logical function that enables near real time control and optimization of onboard control functions and trackside control functions via data collection and actions. It may provide an environment for AI/ML model running. It may host applications which identify the data to be consumed and provided. The Near real time RCU control is steered via policies and data provided via Orc interface from nonreal time RCU.

Ocloud interface between RMEC and MO framework is used for operation and management. It enables the deployment and life cycle management of cloudified functions that run on RMEC. The Ocloud management services may follow existing ETSI standards for Network Function Virtualization (NFV).

Orc interface is between Nonreal time RCU in MO and Near real time RCU functions. It supports three types of services: policy management service, information service and ML model management service. The Orc Application Protocol is based on REST (Representational State Transfer) solution and uses HTTP procedures and JSON objects. It exposes Application Programming Interfaces (APIs) for Orc services. The Orc policies are not critical to train and trackside control, have temporary validity, and may handle individual managed element (Onboard train control system Eurobalise, Euroloop, Interlocking) or dynamically defined groups of managed elements.

Omo interface between MO framework and managed elements is for operation and management by which software management, file management, configuration management, and fault management may be achieved.

Unlabeled interfaces are in accordance with [28].

The Nonreal time RCU, the Near real time RCU, the onboard train control system, and the trackside equipment have radio modules to exchange FRMCS information. The FRMCS system provides functionality for secure communication between entities as described in [25].

The proposed intelligent RBC architecture supports at least three control loops involving different RBC functions:

- Nonreal time control loops running at the Nonreal time RCU level
- Near real time control loops running at the Near real time RCU level
- Real time control loops running at the level of Onboard train control system, Eurobalise, Euroloop, Interlo-cking.

Control loops run simultaneously at different levels and may interact or not with each other. The control loop timing depends on the use case. Typical execution time for use cases involving the nonreal time control loops are 1 or more seconds; the near real time control loops are in order of 10 milliseconds and more; control loops in the managed elements can operate below 10 milliseconds.

The role of the logical units in the proposed RBC architecture is illustrated by the following use case. The use case provides the motivation and description for train speed control based on preventive maintenance and inspection of railway tracks.

There exist number of studies on dataset analysis related to maintenance of railway tracks [15]. The considered use case is based on the data set in [29]. In [29], it is presented a sensor system which uses optical fibers for collecting information about track performance. Information about the mechanical behavior and the state of railway track may be achieved by trackside monitoring of railways. The performance of the railway track varies significantly along the track length due to changing support conditions. The knowledge about this performance helps in track maintenance and in some cases may be critical for train speed along the track.

The goal of the use case is steering of the train speed based on knowledge about railway track performance. The actors involved are as follow. The Nonreal time RCI has policy control function and functions related to ML model training and update, the Near real time RCU has the responsibility to enforce the policy, to provide policy feedback, and to rum the ML models, the Onboard train control system provides control functions and trackside equipment provides measurement data, and MO exposes collection and control as a termination point of Omo interface.

Fig.2 illustrates the procedure of ML model training and deployment. As preconditions, the collection and control functionality in MO has established data collection and sharing process, and the Nonreal time RCU has access to this data, the Nonrealtime RCU monitors track performance by collecting the relevant track performance events from managed elements via MO.

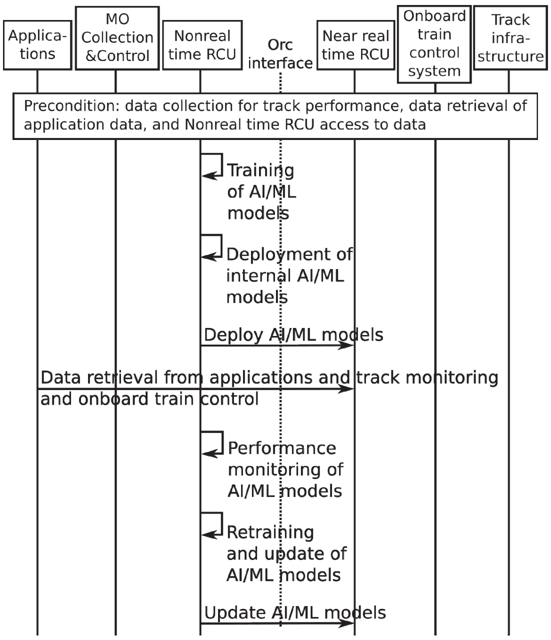

Fig.2 Train speed optimization AI/ML model training, deployment, and update

1. Upon detection of operator specified event or trigger condition, the Nonreal time RCU accesses the track performance measurements and train speed data from MO reports and may decide on either initiating training of a new AI/ML model or modifying an existing one.
2. The Nonreal time RCU executes AI/ML model training, obtains track performance related models, and may deploy train speed policy model internally. Examples of models that can be used at the Near RT RCU are track performance prediction model and train speed mode.
3. The Nonreal time RCU deploys or updates the AI/ML model in the Near real Time RCU via Omo interface.
4. The Near real time RCU stores the received AI/ML models.
5. The Nonreal time RCU may configure, if required, specific track performance measurement data to be collected to assess the performance of the AI/ML models and to update the model in the near real time RCU based on evaluation of performance and retraining of the models.
6. The procedure ends when operator-specified event or trigger condition is satisfied.

As a post condition, the Near real time RCU stores the received track performance ML models and executes the models for dynamic optimization of train speed control function in the Near real time RCU.

Fig.3 illustrates the procedure for rail policy generation and performance evaluation. As a precondition track performance related models have been deployed in the Nonreal time RCU and Near real time RCU.

1. The Control center wants to generate train speed policy or to optimize the AI/ML models.
2. The Nonreal time RCU sends the train speed policy to the Near real time RCU via Orc interface.
3. The Near real time RCU receives the train speed policy, infers the track performance AI/ML models and translates the policy into train control commands for train speed optimization.
4. The Near real time RCU sends the train speed policy to the onboard train control system.
5. The onboard train control system enforces the policy received from the Near real time RCU.
6. The Nonreal time RCU may optionally receive train speed policy feedback from the Near real time RCU and track performance measurements data from MO to assess the performance of train speed optimization function in the Near real time RCU, and to update the train speed policy.
7. The procedure ends when operator-specified event or trigger condition is satisfied.

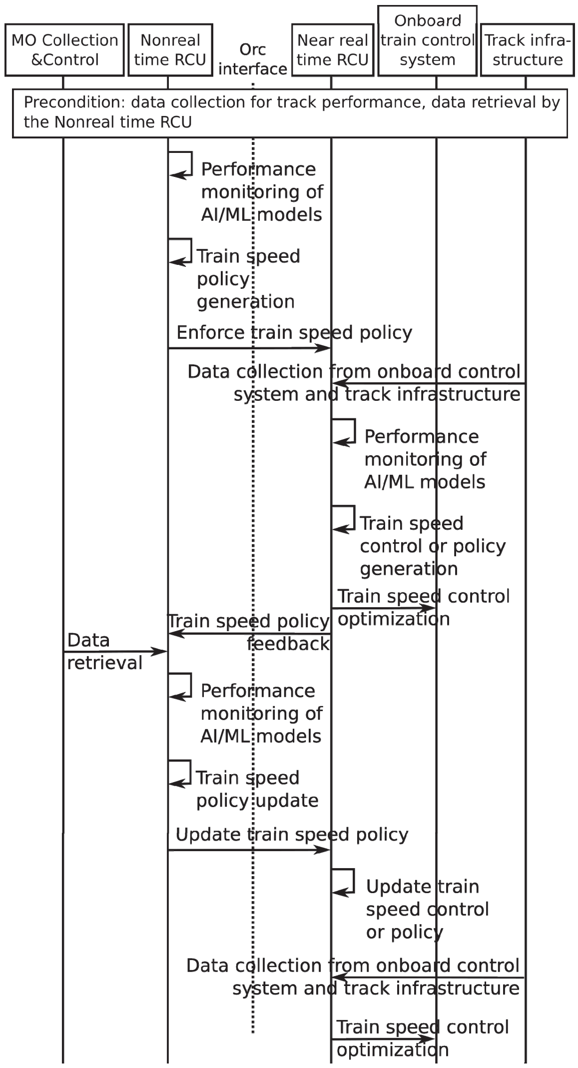

Fig.3 Train speed policy generation and performance evaluation

As a post condition, the Nonreal time RCU monitors the performance of train speed control optimization function in the Near real time RCU by collecting and monitoring the relevant key performance indicators in the onboard train control system.

The research focus is on Orc interface, so the next section provides more details on this interface.

VI. Implementation Issues

The proposed architecture of intelligent RBC includes a Nonreal time RCU and a Near real time RCU which are connected through the Orc interface. The Nonreal time RCU resides in the MO layer that also handles deployment and configuration, and data collection from train and trackside equipment. In the MO layer there also reside functions that handle AI/ML training and deployment, for example ML model training and update, and functions for deployment of ML models and other applications. The Nonreal time RCU in the MO Layer may have access to data other than that available in trackside and onboard train control functions and this enrichment information can be used to enhance the railway guidance and optimization functions. The purpose of the Orc interface is to enable the Nonreal time RCU function to provide policy-based guidance, ML model management and enrichment information to the Near real time RCU function so that the railway operation be optimized under certain conditions.

Based on observables (events and trigger conditions provided over Omo interface), the Nonreal time RCU defines policies that are provided to the Near real time RCU over the Orc interface. The Nonreal time RCU manages the Orc policies based on Orc policy feedback, and on the status of train and trackside equipment parameters provided over Omo. The Nonreal time RCU uses the Omo observables to continuously evaluate the impact of the Orc policies towards fulfillment of railway intent and based on internal conditions it decides to issue/update Orc policies.

The Near real time RCU functions is based on its internal functions or applications, the configuration received over Omo and the temporary policies received over Orc. The information service can be used to support the policy enforcement via in the Near real time RCU. The enrichment information which is provided in addition to the generally available information can enhance performance of railway operation and may be gathered from different sources. MO collects information from internal and external sources. The Nonreal time RCU provides enrichment information to the near real time RCU through the Orc interface. The Orc interface is used to discover, request, and deliver enrichment information.

The protocol stack of the Orc interface is shown in Fig.4. IP transport is used as a transport network layer and the reliable message transfer is based on HTTPS on the top of TCP/IP. The application layer protocol is based on a RESTful approach where railway policy statements are formatted in JSON.

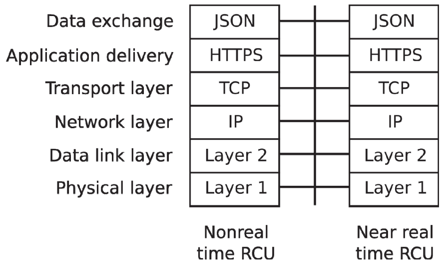

Fig.4 Orc protocol stack

In REST, any entity is represented as a resource which can be created (HTTP POST method), updated (HTTP PUT method), deleted (HTTP DELETE method), and read (HTTP GET method). Fig.5 shows the URI structure of railway policy resources.

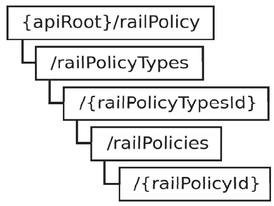

Fig.5 Rail policy resource URI structure

Table I provides an overview of the railway policy resources and the applicable HTTP methods

TABLE I. RAILWAY POLICY RESOURCES AND METHODS OVERVIEW

Resource name	Resource URI	HTTP method	Description
All railway policy type identifiers	/railPolicyTypes	GET	Retrieves all railway policy type identifiers
Individual railway policy type	/railPolicyTypes /{railPlicyTypeID}	GET	Retrieves railway policy type
All rail policies from a certain type	/railPolicyTypes /{railPlicyTypeID}/ railPolicies	GET	Retrieves all railway policies from a certain type
Individual railway policy	/railPolicyTypes /{railPlicyTypeID} /railPolicies /{railPolicyID}	GET POST PUT DELETE	Retrieves a railway policy Creates a railway policy Updates a railway policy Deletes a railway policy

Fig.6 shows a model, representing the railway policy life cycle as seen by the Nonreal time RCU.

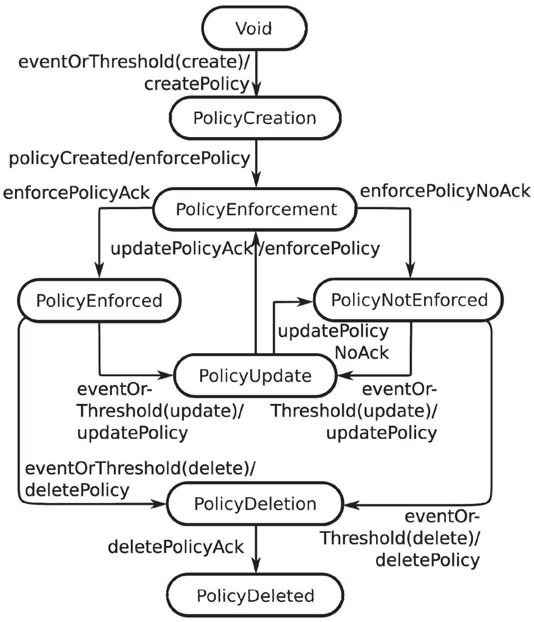

Fig.6 A model representing the railway policy lifecycle.

A railway policy is created, updated, or deleted upon a predefined event or threshold condition. A created or updated railway policy may be enforced or deleted.

VII. Conclusion and Future Work

The paper presents a new disaggregated architecture of intelligent Radio Block Center in a ETCS system. The disaggregation is based on the separation of RBC nonreal time functions from RBC near real time functions and enables embedding intelligence. A use case illustrates applicability of the proposal. Some implementation issues are discussed.

The proposed intelligent RBC architecture supports open interfaces between the logical functions implemented on general purpose hardware. It allows also Nonreal time RCU and Near real time RCU software and hardware from different vendors. Disaggregation and open interfaces between decoupled RBC components provide efficient interoperability between multiple vendors. Another major principle of the proposed intelligent RBC architecture is RBC function virtualization, which reduces costs. The Nonreal time RCU and Near real time RCU improve the embedded intelligence.

Future work will be concentrated on the interface between nonreal time and near real time functions. In addition to policy management, this interface has also functionality for provisioning policy feedback information and enrichment information from external sources that cannot been gathered within the railway network. The purpose of enrichment information is to enable the Near real time RCU to improve its railway operation optimization performance by using information provided by the Nonreal time RCU. There are different type of enrichment information and the Near real time RCU can discover available enrichment information types and request delivery. Other details on the interface between nonreal time and near real time functions include specification of policy related procedures and enrichment information transfer procedures. Further, the interface performance may be evaluated by emulation, e. g. to assess the injected latency.

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