Next-Generation Connectivity in a Heterogenous Railway World

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***Abstract*— Global System for Mobile communication – Railway (GSM-R) is widely used for operational communications between train and signaler. However, there is a need to define a successor that addresses: obsolescence, radio spectrum demand and the enabling of a range of emerging digital applications such as radio-based signaling and Automatic Train Control (ATC). Therefore, the International Union of Railways (UIC) started the initiative to develop the Future Railway Mobile Communication System (FRMCS). This paper describes an Adaptable Communication System (ACS) that is being developed jointly by industry and railway operators as a possible successor covering all types of railways and all aspects of the FRMCS. A pragmatic approach is suggested that considers diverse railway settings and makes use of various radio access technologies. Countries, geographical regions and infrastructure managers differ concerning available radio technologies, but use of a suitable ACS could pave the way towards innovation in the railway sector. For this adaptive concept we discuss several network models and enhancements including satellite communications (SatCom), Software-Defined Networking (SDN) integration and antenna systems that support multiple bearers in one. For SatCom a software defined radio (SDR) prototype using random access is presented that is able to fulfill the requirements of ETCS. We found that SDN can be used for dynamically changing the access technology for critical and non-critical railway use cases. Furthermore, we present an antenna prototype that can be used for 5G, GSM, WLAN and LTE in parallel which saves limited mounting surface on the train.**

***Index Terms*— Adaptable Communication System, GSM-R, Multi-Band Antenna, Railway Communication, Satellite Communication, Software Defined Networking, Future Railway Mobile Communication System**

I. INTRODUCTION

GSM-R is the long-standing de-facto operational railway communication standard used to provide voice communication and the European Train Control System (ETCS) services for digital signaling to trains. However, the emergence of new use-cases and advanced applications such as Automatic Train Control (ATC), moving block, virtual coupling and train integrity that are developed by railways to improve the performance will require broadband connectivity among many devices and additional features (resource management, IP connectivity, security, etc.) which cannot be supplied by GSM-R. Additionally and most importantly, vendors announced GSM-R obsolescence by 2030. These have stimulated a need to develop a successor led by the International Union of Railways (UIC) under the Future Railway Mobile Communication System (FRMCS) initiative. The FRMCS User Requirements Specification (URS) [1] was published in 2020 describing a wide range of functional requirements and service characteristics of the communication system. The services have been categorized into critical, performance, and business-related services. It is currently used as the basis for standardization work in the Rail Telecommunications Technical Committee of the European Telecommunications Standard Institute (ETSI TC-RT) and the 3rd Generation Partnership Project (3GPP) working group SA1 (system architecture – functional). As part of this initiative, a dedicated frequency band has been assigned, i.e., in the ECC Decision (20)02 for migration to FRMCS:

- 974.4 - 880 and 919.4 - 925 MHz
- 1900 - 1910 MHz (TDD)

European rail infrastructure managers (IMs) published a position paper for strategic deployment of 5G connectivity and spectrum for rail together with railway operators and rail industry [2].

An Adaptable Communication System (ACS) for train to ground communication is answering these needs and matching the requirements of FRMCS URS as it is developed as one of the technology demonstrators within the Innovation Program 2 (IP2) of the European Horizon 2020 research and innovation initiative Shift2Rail and it is being delivered under the X2Rail suite of projects. Off-networks solution have been investigated in the same context in [3]. The ACS developments will directly compliment the FRMCS project and ETSI standardization as collaborations are established. It is aligned with the position paper and its targets as well as FRMCS, whilst exploring different business models considering dedicated and public networks.

Roll-out of new telecoms infrastructure e.g. across the whole of Europe, means equipping several thousand kilometers of tracks and thousands of trains with new technology. Countries, geographical regions and IMs have a range of specific

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requirements and an evolutionary approach needs to consider the availability of different bearers in different locations. It will take time before the final stage is reached and therefore, the ACS has been developed as a multi-bearer system that can make use of any supported communication technology such as 3GPP's 4G and 5G, satellite communication (SatCom), Wi-Fi and millimeter-wave wireless technologies [4]. This is a pragmatic approach because the railway sector is heterogeneous. Dependent on Quality of Service (QoS) parameters, the ACS selects the appropriate set of bearers that are used for an application. Thereby, bearers can be used as back-up and alternatives to each other, or complementary to operate in parallel to increase net coverage and capacity. The ACS is bearer agnostic and independent of the digital applications and hence enables graceful migration from GSM-R.

The ACS follows the FRMCS reference architecture described in [5] and has been implemented in three separate demonstrators: one for highspeed/mainline, one for urban/suburban, and the last for regional/freight lines. The demonstrators are planned to be tested in the field within the final phase of the X2Rail projects in 2023. Both ACS and FRMCS share similar objectives, however, while FRMCS focuses on 3GPP standards and allows for bearer flexibility, the ACS carries bearer independence as its most robust feature. In fact, the ACS does not make a difference between 3GPP and non-3GPP standards as it interfaces at the bearer IP layer (supporting the technology independence). The approach followed by FRMCS and the ACS is not mutually exclusive: the ACS provides bearer independence and QoS support for applications without entirely relying on interoperability specifications such as those provided by the 3GPP, as FRMCS does. This means it fosters innovation based on technologies that are already available or easy to deploy dependent on an IM’s specific requirements.

Considering the heterogenous railway environment and the ACS context, in this paper we investigate three topics of interest related to the ACS implementation: (I) the use of SDN for the ACS that enables network slicing and can manage traffic forwarding, (II) an antenna system enabling the simultaneous use of multiple bearers at the physical layer while accounting for constraints in train roof space, (III) and the integration of SatCom as bearer offering coverage in underserved areas. As background, first the general concept of the ACS in line with the FRMCS URS is presented.

III. ACS ARCHITECTURE

A high-level block diagram showing the ACS concept is depicted in Figure 1. Applications include signalling, (automatic) train operations and internet services. Train speed can vary from stations to highspeed lines between 0 and 500km/h. The applications can connect to and from the train using dedicated or public telecommunication networks as discussed in the next section. The ACS supports a wide range of communication bearers (e.g. 4G LTE, 5G, Wi-Fi, SatCom) that connect onboard-side with trackside. Note that three exemplary bearers are illustrated, as mentioned the ACS is in general bearer agnostic and not limited on the number.

The ACS consists of the session control, the service layer and the transport layer and decouples the applications from the access technology. Services and functions offered include registration, authentication, session and service management as well as providing dynamic bearer selection, routing, handover, multipath, and QoS control of the various connected bearers. The value-added features of the ACS, such as the increased resiliency and capacity, can be achieved for example by utilizing multi-path communications protocols such as Multipath TCP (MPTCP), 3G-PPP ATSSS or QUIC, where application data packets may be routed over several wireless bearers and track-side packet data networks as investigated in [6]. Similarly, for cases that require the UDP protocol or real-time sensitive use cases, the RaSTA protocol is required, where it creates a redundant UDP tunnel based on bearer redundancy. Its’ entire operation is transparent to the users, authentication, and data security endpoints. Although, not illustrated in Figure 1, the counterparts of the track-side functions are implemented also on-board.

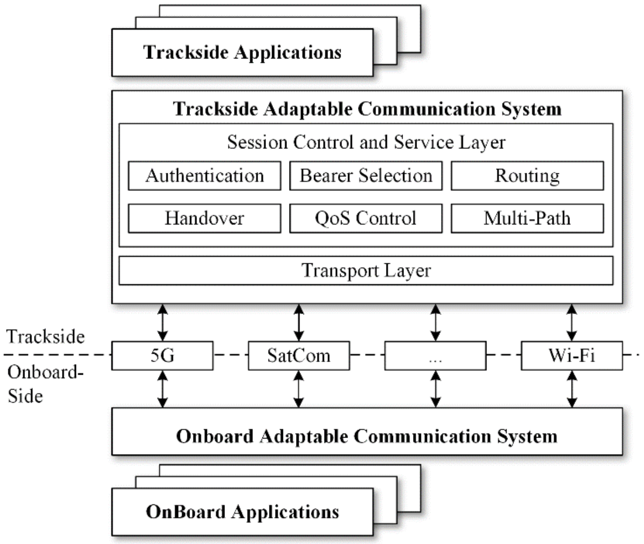

Figure 1. Adaptable Communication System Block Diagram. The Application connect to the onboard and trackside ACS which manages the communication via multiple bearers transparently.

The heart of the ACS is the QoS control block, which continuously monitors the QoS demand by the applications and the available QoS from the bearers, then enables the best possible resource allocation among them. The bearers add resiliency and capacity. Since the ACS allows parallel use of multiple access networks (bearers), it must implement vertical and horizontal network handover to guarantee communication availability. In this way, the use of the network type is transparent to the applications and is based on the QoS mechanisms and not the technology. For bearers not offering channel information for QoS, typical values for the bearer technology, or measurements along the track can be used. The application registers with the ACS, along with the set of required QoS parameters such as data rate and latency. For example, in regional railway use cases, the ACS enables the use of Wi-Fi and mobile networks in stations and if those are not available along the track switches to SatCom to continue operation. If multiple bearers are available they can be used in parallel. For instance, latency requirements need to be fulfilled or they are used in a complementary manner to increase bandwidth and improve performance. Since the bearers are independent they need to be investigated independently. For instance, channel investigations on 3GPP technologies have been performed by [7] and general train channel emulation has been investigated by [8].

Both traditional and SDN devices can be used in the onboard and trackside networks (either as part of the ACS like a virtual switch or a physical switch within the LAN). The use of SDN switches and controllers implements the selection of multiple bearers, flow rate limitation, real-time flow blocking and bearer differentiation of different flows. See Section V for a further explanation.

In the first phase, the ACS was evaluated in the lab along with the enabling technologies presented in the remainder of this paper. Three reference implementations are depicted as demonstrators, each considering different scenarios: main-line/highspeed, sub-urban/urban, regional/freight. The demonstrators reflect typical use cases for their scenarios including dedicated sets of bearers that can be found in the field. Results show that the demonstrators are able to address requirements of the FRMCS. The lab evaluation will be followed by field tests in late 2022/23 using four tracks in France, UK, Italy and Germany. At each track different bearers will be available including Wi-Fi, 4G, 5G and SatCom.

IV. NETWORK MODELS

The dominant network model for GSM-R was that of a dedicated private network, so that railway operators owned and operated the communication network. Given the ACS approach, there are more degrees of freedom in defining a network approach. Five candidate network models have been defined. For all the models, service quality, availability, reliability and security must meet the railways' operational needs.

Dedicated Mobile Network - For this, the entire network is under the ownership and control of the IM, as is the case for current GSM-R deployments. Thus, the IMs can design the network according to the operational requirements.

Dedicated Network with Supplementary Public Network – Additional bandwidth demand can be accommodated by using a supplementary network operated by a Public Network Operator (PNO) on top of the dedicated railway network. Mission critical services would be made available via the dedicated network. The supplementary public network could be used for supporting non-critical services that require higher data rates, e.g., passenger connectivity or real-time video applications. Public SatCom networks offer an alternative to PNO's for increased coverage and availability.

Dedicated Network RAN Sharing with Public Network - Sharing the Radio Access Network (RAN) could result in a cost reduction, as the RAN is the most expensive part of a mobile network. RAN sharing encompasses the joint use of sites, masts, antennas, and power supply, but can also include transmission-related equipment. The usage of both dedicated IM spectrum as well as public spectrum owned by the PNO is possible. Given an appropriate agreement between the IM and PNO, the IM retains control over the network and the user management. The Core Network (CN) remains under the ownership of the IM. RAN sharing agreements are not only attractive for IM and PNO from a financial point of view, they also address the issue of limited social acceptance of mobile technology sites by the public.

Public Network, IM as MVNO - In this scenario, the IM does not operate its own dedicated wireless communication infrastructure anymore but acts as a Mobile Virtual Network Operator (MVNO) using existing public infrastructure to provide its services. The MVNO retains control over the management and authentication of users, however, coverage and availability will depend on the PNO. 5G offers the option of multi-tenant slicing which would also facilitate the prioritization of mission-critical traffic or the handling of railway specific voice services.

Public Network - In this operational model, the IM does neither own, nor operate a dedicated network and instead relies solely on the services of a PNO. Availability and QoS depend entirely on the PNO, which results in strict service level agreements to allow the critical operation of trains. Security issues must be considered as the IM would rescind control of user network authentication to the PNO.

When comparing the different models, it is clear that owning a dedicated mobile network offers maximum flexibility to an IM. It may also be politically desirable that there is no interference from market forces such as company ownership or prices. However, it is the costliest solution and given that 5G PMO networks are available it is not easy to justify such an investment. Therefore, hybrid approaches are most likely: IMs may own mobile networks for specific tracks, they may own the core network and cooperate on the RAN and in some regions, they may choose PNO services. In the following we present three aspects that support with heterogenous setups. Software-Defined Networking (SDN) for network slicing, a single antenna supporting a set of bearers, and SatCom which would not require any trackside infrastructure at all.

V. SOFTWARE-DEFINED NETWORKING

Since the publication of the OpenFlow protocol in 2008, SDN has been associated with the next-generation of telecommunications networks.

There are two main reasons to integrate the ACS and OpenFlow switches: (i) to demonstrate the flexibility of the communication system and (ii) proof that the ACS can modify the traffic treatment and rate limit, certain tenants, at runtime. Two SDN switches are placed in the train and trackside networks. When the ACS informs the controller about the available resources, the controller instructs the switch to distribute the traffic according to a prevailing scenario or limit the data rate. The controller implements a different profile (slice) for critical and non-critical traffic types in terms of priority and data rate.

The train and trackside networks include an Open vSwitch (OVS) [9], as described in the following two use cases. In the first use case, the switch is connected to a controller that manages traffic forwarding using different access modules attached to the ports. In the train, OVS can be integrated into the ACS, and the SDN controller commands OVS to forward the traffic via one or more access bearers. In the second one, when integrated into the train LAN as a software (OVS) or hardware switch, the controller can command the switch to distribute traffic across different ACS devices.

In regard to the ACS test setup, the SDN controller was connected to two virtual machines (VMs) representing onboard and trackside networks. Both VMs used the Ubuntu 20.04 operating system and Mininet 2.3.0 with OVS 2.13.0.

In Figure 2, CCTV (critical) and passenger video call (non-critical) traffic is transmitted train-to-ground at 8Mbit/s and 2 Mbit/s, respectively. The flows belong to two different slices and are assigned different resources. Slice 2 is guaranteed 4Mbit/s (blue line) when resources decrease. Slice 2 is assigned more resources when conditions allow for it. Slice 1's traffic (non-critical) is rate-limited (red line), without being assigned more resources later on. An authorized application running in the train can configure the network by assigning the resources that each access technology can offer based on previous measurements. In addition to the metered traffic, the SDN controller can dynamically change the access technology used for critical traffic using bearers that usually impose lower latencies at a particular railway track section.

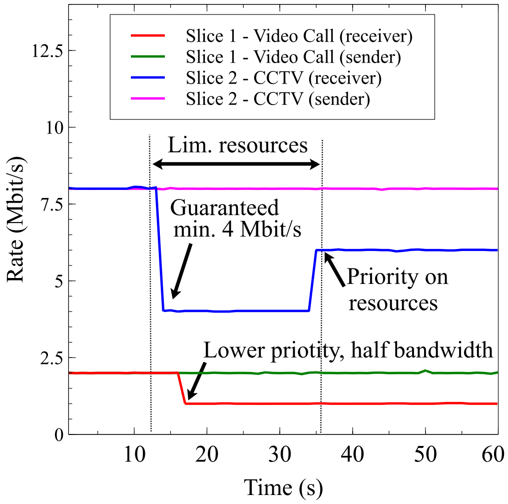

Figure 2. Rate-limited traffic. Non-critical passenger video call (slice 1) and critical CCTV (slice 2) with guaranteed 4 Mbit/s.

VI. ANTENNA INNOVATION

The ACS is intrinsically adaptable in terms of dynamic bearer selection and for its implementation both onboard and trackside, novel antenna systems considering these specifications while maintaining antenna dimensions or footprint equivalent to currently deployed GSM-R antennas should be developed.

An antenna system for the ACS should thus be able to deal with multiple bearers simultaneously whilst providing a high level of isolation between them. One of the common techniques is to use co-located antennas, each supporting a different communication standard [10]. This solution is however bulky and requires matching circuits to reach the ACS communication system specifications. Biasing circuits might also be required resulting in low efficiency and narrow band coverage. Complex solutions based on mechanical arrangement and/or active devices such as diodes, RF switches, actuators, and filters can also be considered to achieve reconfigurability and isolation. To maintain the value of an ACS solution and its implementation onboard, a new antenna concept beyond the classical miniaturization techniques is proposed such that a single radiating element can support multiple frequency bands and bearers through different ports while providing a sufficient level of isolation between them. Hence the multiple-port antenna is a desired feature.

The proposed antenna consists of three feed points of a single radiating element which acts as a radiator. Modal analysis has been applied to the radiating element: to find the significant resonant modes, the preferred feed position at multiple locations around the radiator can support together with a high level of isolation between the ports due to modal orthogonality.

Figure 3 presents the concept of the proposed multi-bearer antenna with an ellipse-shaped radiating element supporting three ports. The ports are designed to support various frequency bands in the cellular and non-cellular range and provide isolation to the other bands.

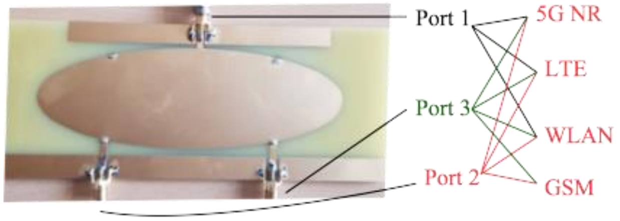

Figure 3. Prototype of proposed Multi-band Elliptic Monopole Antenna with multiple ports. The Antenna provides three ports that enable the connection for GSM, LTE, WLAN and 5G NR.

Table 1 presents the measured isolation levels between port 1 and port 2 or 3 for the LTE, WLAN and 5G NR bands. As shown in the table, the minimum isolation is -18.8 dB which is below the required level of -15dB [11]. The 3D radiation patterns exhibit the familiar ‘doughnut’ shape with a maximum gain that would be along the direction of the track when mounted on a train.

Standard	**Isolation (Between Port 1 and 2)**		**Isolation (Between Port 1 and 3)**	
	Frequency	**level in dB**	**Frequency**	**level in dB**
4G LTE	2.5-2.69 GHz	< -19 dB	2.5-2.69 GHz	< -20 dB
WLAN	2.4 GHz	< -18.4 dB	5.3–5.5GHz 5.85– 6GHz	< -23 dB < -31 dB
5G NR	3.6– 4.5 GHz	< -25 dB	--	--

Table 1. Measured isolation levels between different ports of the proposed antenna

VII. SATELLITE COMMUNICATIONS FOR RAILWAY CONNECTIVITY

SatComs have the main advantage of covering large areas with low capital expenditure compared to the terrestrial infrastructure required to cover the tracks along Europe. This makes it interesting for several use cases in the railway domain:

- IoT connectivity, e.g. to connect smart way-side objects.
- video connectivity such as for monitoring stations in remote areas and connecting cameras to a centralized control center.
- virtual balises for assisting next generation signaling schemes.
- passenger communications, in combination with terrestrial technologies, especially in rural areas.
- a fallback solution for when terrestrial infrastructure is damaged.
- reducing track side vandalism since there is a reduction in infrastructure.
- a compliment to terrestrial communication system and as a backup in case of 'not spots' or during hand-over procedures.

Motivated by the later five points that fit the ACS setup, we investigated SatCom as bearer technology in a lab environment. The bearer is illustrated in Figure 1 and includes the full communication technology. Main goal is to make use of this bearer to complement terrestrial technologies in order to fulfill QoS requirements.

Future, upcoming systems and recent advances make SatCom a promising solution. Very High Throughput Satellite Systems (VHTS) offer an increase in data capacity to several Tbits/s, which make it even more attractive for video-based applications. Furthermore, for the next years capacity of SatComs mobile broadband services is expected to increase, which would appear to be attractive for railways. Upcoming Low Earth Orbit (LEO) constellations consisting of thousands of satellites have not yet been practically proven in mobile environment but are expected to reduce latency that satisfies the latency requirements of FRMCS (150ms for voice, 3.5s for ETCS). In LEO, coverage is improved in northern countries making it more attractive. SatComs are included in the current release of the 3GPP 5G standard, helping it to become more applicable for railway applications. SatComs can take advantage of the intrinsically better cost effectiveness in case of multicast connectivity, to be adopted to broadcast alarms and service information, for video/audio distribution to passengers, etc.

Previously, systems have not been able to satisfy the requirements of the FRMCS as pointed out by [12]. Disadvantages in serving railways have been: operational expenditure; availability; use of dedicated handheld devices; latency due to the round-trip time of the signal in case of Geostationary and Medium Earth Orbit (GEO, MEO) systems which especially impacts voice communications. The latency in these cases is mainly determined by the traveling distance between earth and satellite (~100-250ms), other delays are neglectable. The best solution found was a theoretical MEO system which only lacked a suitable security mechanism in order to fulfill the requirements. The proposed setup is using C-band and a MEO constellation of 10-15 satellites. The channel conditions are challenging in the railway environment since, in addition to the usual channel impairments of a SatCom link, slight reduction of availability may occur due to partial signal occlusion due to overhead infrastructure. Spatial diversity is, for instance, a solution to address this [13].

In order to demonstrate the applicability to the railway sector and perform investigations in a lab, a prototype based on Software Defined Radio (SDR) for SatCom has been implemented which offers flexibility and may be adapted to many different telecommunication systems [14]. Higher protocol layers have been simulated and results presented in [15]. For our investigations we focus on a single setup described in the following which is designed to support signaling applications such as the ETCS digital train protection system. We focus on these applications since current SatComs can accommodate their requirements.

The prototype consists of a gateway which is connected to the track-side of the ACS and a user terminal connecting the train-side as illustrated in Figure 1. User terminal and gateway are connected by a satellite return link (from train to gateway via satellite), and forward link (from gateway via satellite to train). We provide a MAC and a PHY layer implemented in SDR for each the gateway and the user terminal running on dedicated PC. Two USRP N210 are used as radio-frequency frontend to convert the data into the desired radio waveform. A satellite channel emulator adds a fixed delay of a GEO satellite (250ms per link) and a certain packet drop rate. We assumed clear sky conditions without any train specific channel impairments. We assume fades due to overhead infrastructure will be addressed by spatial diversity and tunnels will result in a full loss of the signal and bearer switch.

We assume a wide-band system for the forward link which is not limited by resources. For the return link, the situation is different where multiple users transmit in an uncoordinated way with short signaling messages, as is the case for ETCS. Furthermore, in order to provide a cost-efficient solution enabling equipment for a large number of trains, the terminal complexity must be kept low. Random Access (RA) schemes are a suitable solution for such characteristics and fit better than typical applied TDMA schemes. We implemented Contention Resolution ALOHA (CRA). CRA belongs to a family of modern RA schemes for data transmission and uses proactive replications of packets and successive interference cancellation for achieving a high spectral efficiency. No channel sensing or any advanced handshake procedure to grant resources are necessary. In order to resolve possible channel contention when multiple users (trains) access the same resource at the same time, advanced signal processing, error correction and interference cancellation are exploited. All these advanced techniques entail additional complexity that is confined to the gateway receiver side. Other RA schemes are also possible, for instance the RA scheme of DVB-RCS2. The SDR approach allows adoption of different systems.

The packet loss rate and spectral efficiency as a function of the aggregate channel load of CRA determined by simulation is shown in Figure 4. Two replicas per message are transmitted by the users, and a rate of $R = 1.5$ bits/symbol is adopted, which refers to a coding rate of ¾ and QPSK modulation. An SNR of 6 dB at the receiver input is assumed for all incoming replicas. Although not targeted in a practical system, a packet loss rate of 10^{-1} can be supported up to 1 bit/symbol channel load with CRA, compared to only 0.2 for the baseline ALOHA protocol as the simplest RA protocol.

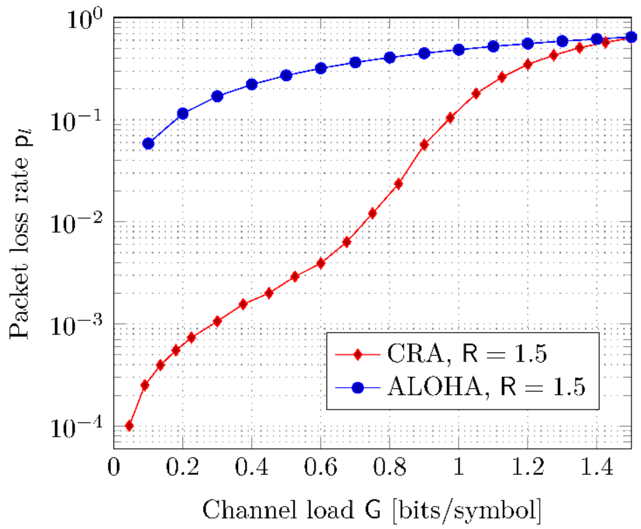

Figure 4. Packet loss rate of CRA and ALOHA as a function of the aggregate channel load G. A rate 1.5 bits/symbol is adopted referring to a coding rate of ¾ and QPSK modulation.

Figure 5 shows the results of the SDR prototype connected to the ACS and using recorded ETCS traffic from a real train connection in Italy. It shows a lower transmission rate for the return link which is expected due to the increased complexity of the successive interference cancellation algorithm. The data rate is still above the limit defined in the user requirements for ETCS hence we could verify that the system can be used for ETCS traffic.

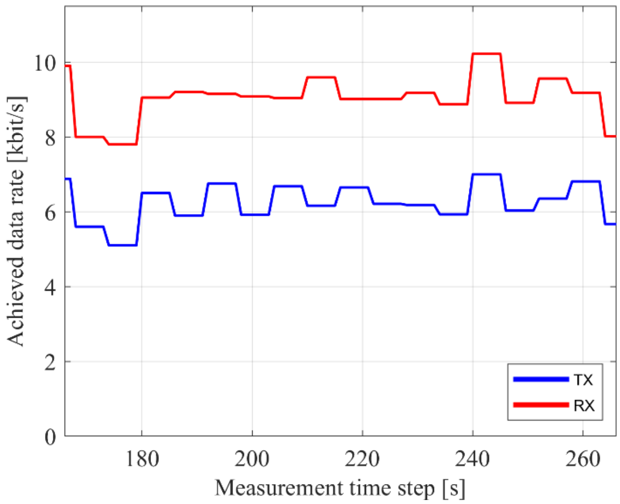

Figure 5. Achieved data rate (kbit/s) over time of the SatCom SDR prototype using CRA. Transmitted and received data rate of the prototype are shown.

VIII. SUMMARY AND OUTLOOK

The ACS described in this paper is helping to drive future digital railway connectivity. It enables this application field to fully benefit from technologies beyond GSM-R by demonstrating the benefits of a bearer agnostic approach and decoupling digital applications from the communication system. SatCom as a bearer for serving railway connectivity as well as a new antenna concept were shown, in addition to SDN technology for routing and security. Furthermore, different network models have been outlined and an antenna design supporting multi-bearers to cope with limited space requirements.

The ACS has been implemented in three demonstrators each configured for serving highspeed/mainline, urban/suburban and regional/freight lines. The developments including the SatCom prototype, the SDN setup and the antenna has been evaluated in the lab. Within the final phase of the X2Rail projects in late 2022/23 the demonstrators will be moved to the field to evaluate the performance in an operational environment. The findings of the lab evaluation and the field tests will directly influence the FRMCS project and ETSI standardization as collaboration is in place to support this. For future work, AI based bearer selection can be investigated, or the extension of the SDR to terrestrial systems.

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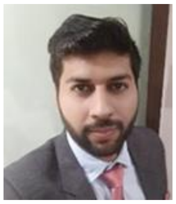

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