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5G-powered FRMCS

Ubiquitous and uninterrupted connectivity for future rail transportation

To develop more sustainable transportation systems, societies worldwide are making efforts to increase the share of rail in transporting people and goods. Europe, for example, aims to reduce greenhouse gas emissions and become climate neutral by 2050. To this end, the European Green Deal, a set of policy initiatives by the European Commission, aims to cut emissions while improving people's well-being [1]. Recognizing that the transport sector represents 25 percent of the world's emissions, rolling out cleaner, cheaper, and healthier forms of private and public transportation is an important part of the European Green Deal. To mark the importance of increasing sustainability within the transport sector, 2021 was the European Year of Rail. The European Year of Rail highlighted that rail is one of the most sustainable, innovative, and safest transportation modes available today and will remain so in the foreseeable future [2]. With more than 200,000 kilometers of railway lines in the USA, 150,000 kilometers in Europe, and more than 100,000 kilometers in India, businesses and freight carriers can benefit from low-cost and increasingly competitive transportation solutions while reducing their carbon footprint [3]. For passenger traffic, traveling by rail is safe, as indicated by the extremely low fatalities per billion passengers/km, compared to those suffered by road users.

High-speed train travel is only possible using effective train control. A train driver without train control loses situational awareness and cannot react fast enough at speeds above 180 km/h. In Europe, the standard railway control-command and traffic management system is the European Train Control System (ETCS). This system is currently enabled by the Global System for Mobile Communications – Railway (GSM-R), the standardization of which has been driven mainly by the International Union of Railways (UIC). GSM-R, with its circuit-switched data communication, addresses the needs of critical voice communications and data transmissions for certain rail use cases defined in ETCS. Despite the success of GSM-R, it is becoming obsolete, due to the technological advancements of mobile communications systems, the widespread use of broadband services, and the increasing deployment of 5G cellular networks. 5G capabilities are also creating many new opportunities for railway systems, whether they concern use cases aboard a train, along railroads, or combining the operation of trains, signaling systems, operational centers, and workshops, which enable (semi-) autonomous train operations.

Recognizing the need to gradually replace GSM-R with the modern technology, the UIC has decided to lay the foundations of the Future Railway Mobile Communication System (FRMCS), of which the main goal is to fully digitalize railway operations, support an increasing level of automatic train operations (ATO), and embrace the possibilities offered by 5G without creating a railway specific cellular network technology. Besides these basic goals, FRMCS aims to be cost effective and future-proof, interoperable, and allow seamless migration of GSM-R to FRMCS. To meet these requirements, there are multiple challenges, which are being tackled with FRMCS standardization. This white paper discusses the challenges and opportunities of becoming successful in deploying 5G-enabled FRMCS for the digitalization of railway operations.

Content

FRMCS applications and requirements

To ensure that the requirements arising from railways are addressed by the evolving 5G systems, the UIC has formed an FRMCS functional working group. As an outcome, the working group has specified the user requirements for FRMCS [4]. In the specification document, the applications are grouped into three main categories, that is, (1) applications that are essential for train movements and safety or legal obligations, (2) applications that help to improve the performance of railway operations, and (3) applications that support railway business operations in general. Figure 1 shows different applications which fall into different categories as listed above.

Critical communication	Performance communication	Business Communication
On/multi-train voice call	On/multi-train voice call	Inviting-a-user messaging
Trackside maintenance	Lineside telephony	Emergency help point for public
Shunting communication	Public address	On train/platform wireless connect
Public emergency call	Station/Depots communication	
Platform alerts	Telemetry	
On-train safety communication	Remote equipment control	
Railway emergency	Infrastructure monitoring and control	
Remote control	Real-time video	
Maintenance warnings	On-train/platform communication	
Ground-to-ground voice call	Data transfer	
Automatic train control/operation	Driver advisory	
Possession management	Train departure communication	
Monitoring and control	Broadcast communication	
Train integrity	Messaging services	

Figure 1. FRMCS applications

It is evident that the different FRMCS applications listed in Figure 1 demand exchange of voice, video, and/or data requiring low latency and high reliability communication. 3GPP has specified the performance requirements for these applications in TS 22.289, and they are shown in the Table 1.

Scenario	End-to-end latency	Reliability (Note 1)	Speed limit	User	Payload size (Note 2)	Area traffic density	Service area dimension (note 3)
Voice Communication for operational purposes	≤100 ms	99.9%	≤500 km/h	100 kbps up to 300 kbps	Small	Up to 1 Mbps/line km	200 km along rail tracks
Critical Video Communication for observation purposes	≤100 ms	99.9%	≤500 km/h	10 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
Very critical Video Communication with direct impact on train safety	≤100 ms	99.9%	≤500 km/h	10 Mbps up to 20 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
	≤10 ms	99.9%	≤40 km/h	10 Mbps up to 30 Mbps	Medium	Up to 1 Gbps/km	2 km along rail tracks urban or station
Standard Data Communication	≤500 ms	99.9%	≤500 km/h	1 Mbps up to 10 Mbps	Small to large	Up to 100 Mbps/km	100 km along rail tracks
Critical Data Communication	≤500 ms	99.9999%	≤500 km/h	10 kbps up to 500 kbps	Small to medium	Up to 10 Mbps/km	100 km along rail tracks
Very Critical Data Communication	≤100 ms	99.9999%	≤500 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 10 Mbps/km	200 km along rail tracks
	≤10 ms	99.9999%	≤40 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 100 Mbps/km	2 km along rail tracks
Messaging	-	99.9%	≤500 km/h	100 kbps	Small	Up to 1 Mbps/km	2 km along rail tracks

Note 1: Reliability as defined in sub-clause 3.1 of TS 22.289.
Note 2: Small: payload ≤ 256 octets, Medium: payload ≤512 octets; Large: payload 513 -1500 octets.
Note 3: Estimates of maximum dimensions.

Table 1. Performance requirements of railway scenarios

5G new radio features for FRMCS

5G new radio (NR) was originally designed to support high mobility services requiring high reliability and/or low latency which are in alignment with the performance requirements of railway communications as described above. Some of the 5G NR features, which play a crucial role in railway deployments and their evolution, are listed here.

1. 5G NR has a flexible and robust physical layer design. For example,
    a. Different subcarrier spacings targeting different frequency bands (for example, low, mid, and high bands) provide resilience against an increasing Doppler effect and hardware impairments with increasing carrier frequency.
    b. Dense DMRS patterns enable accurate channel estimation in high Doppler effect scenarios.
    c. A rich set of reference signals (for example, channel state information and sounding reference signals) for channel acquisition enables massive multiple-input, multiple-output (MIMO) operations.
2. The railway applications relying on very critical data communications have latency requirements below 10 ms. The 5G NR features, which support low and bounded latency (for example, UL configured grants, preemption mechanisms, a shorter transmission duration through higher subcarrier spacing and mini-slots, fast retransmissions, and prioritization between critical and non-critical transmissions, and so on), can enable such use cases.

3. 5G NR offers a rich set of features to alleviate the handover-related issues arising from high mobility, for example:
   a. Diverse multi-transmission reception point (TRP) transmission schemes, such as dynamic point selection (DPS), and single frequency network (SFN), which can be employed in railway deployments to reduce the frequency of higher layer handovers
   b. Conditional handovers allow the reduction of handover failures due to high mobility by configuring a user to perform handover operations when certain conditions are satisfied.
   c. The dual active protocol stack (DAPS) feature reduces the service interruption time during a handover down to 0 ms by introducing simultaneous reception of user data from both the source and the target cell before the migration to the target cell.

Spectrum and deployment

Today GSM-R is deployed in the 900 MHz band (termed R-GSM band) and its extension band (termed ER-GSM band). However, the railway industry is planning for a gradual migration, during which GSM-R and FRMCS will run in parallel. This is a challenge, since due to the parallel operation during the transition period, a rail operator cannot simply refarm the entire spectrum currently used by GSM-R to FRMCS. Therefore, either additional spectrum will be needed to support a smooth introduction of FRMCS services running over 5G in parallel or only some parts of the GSM-R spectrum can be re-farmed for FRMCS. Consequently, in Europe, the Electronic Communications Committee (ECC) approved a harmonized use of the paired frequency bands 874.4—880.0 MHz and 919.4—925.0 MHz, and the unpaired frequency band 1900—1910 MHz for railway mobile radio, which includes both GSM-R and FRMCS [5]. Based on this ECC Decision, in addition to the independent operation of FRMCS in the 1900 MHz band, FRMCS and GSM-R can also coexist in the 900 MHz band until GSM-R operation is phased out and eventually FRMCS can be extended to the 2x5.6 MHz bandwidth available. However, it is not clear if the capacity that can be achieved in the 900 MHz band will be sufficient for FRMCS services in dense railway networks since some parts of the spectrum will be used by GSM-R. Moreover, operating FRMCS in the 919.4—921 MHz band has a disadvantage when compared to the 1900 MHz band since it is very close to the uplink part of the 3GPP Band 8 (880 MHz-915 MHz) allocated for the evolved universal terrestrial access (E-UTRA). Therefore, for safety-critical FRMCS applications, it is recommended that the railway industry uses the 1900 MHz band for 5G NR based FRMCS and is supported by the numerical results on the achievable 5G NR latency, reliability, and user throughput below.

As mentioned before, some of the safety-related use cases demand high reliability and throughput with bounded end-to-end (E2E) latency at high train speeds. For instance, very critical video communication use cases demand 10—20 Mbps throughput at train speeds of 500 km/h with 99.9 percent reliability. The 5G NR design allows the use of 30 kHz subcarrier spacing (SCS) in the 1900 MHz band to support the critical video use case for the high train speeds.

Figure 2 shows the uplink (UL) simulation results when using 30 kHz SCS and a bandwidth of 10 MHz available at the 1900 MHz band for the case of 4 transmitter and 8 receiver antennas. It is evident that NR satisfies both the throughput and reliability requirements at low to moderate signal-to-noise ratios (SNRs).

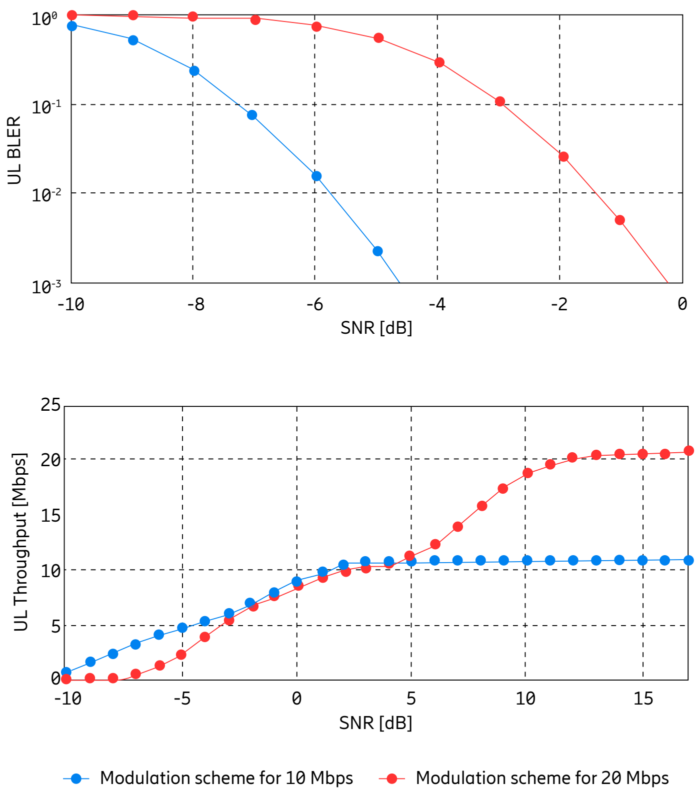

Figure 2. Simulation results for the very critical video communication use case showing UL transport block error rate (BLER) and throughput as a function of SNR

Another demanding use case, very critical data communication, requires extremely high reliability of 99.9999 percent and a maximum E2E latency of 10 ms for throughputs of 0.1–1 Mbps at 40-km/h train speeds. 5G NR with its inherent support for ultra-reliable low latency communications (URLLC) and support of 30 kHz SCS with a 0.5 ms transmit time interval allows up to 3 retransmissions within a duration of 6 ms. Utilizing these 5G NR features, high reliability can be achieved while satisfying the stringent E2E latency. Figure 3 shows the simulation results for this use case using the evaluation assumptions described above and a bandwidth of 10 MHz available at 1900 MHz. It is evident that 5G NR satisfies the requirements at quite low SNRs.

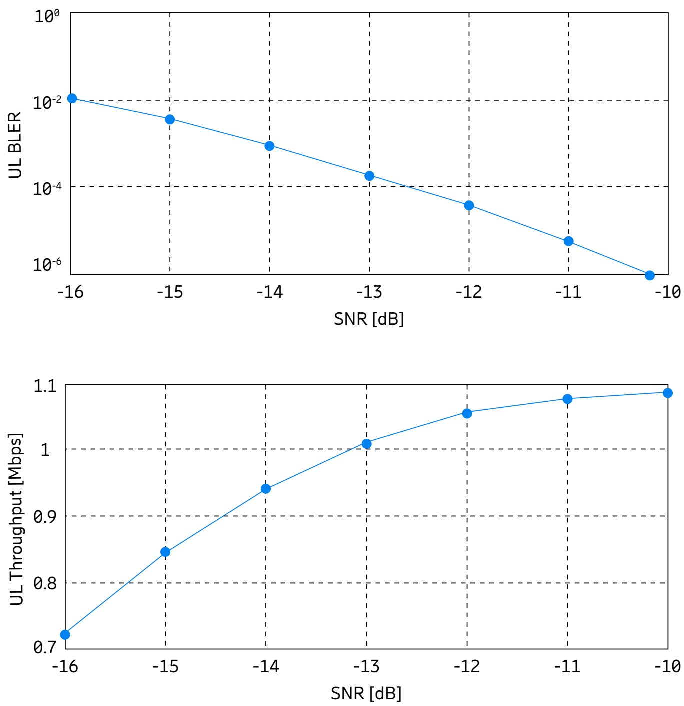

Figure 3. Simulation results for the very critical data communication use case showing UL transport block error rate (BLER) and throughput as a function of SNR

Furthermore, the European Union has established a strategic deployment agenda of 5G road and rail corridors. The ambition of the 5G corridor is to provide 1 GB per second throughput per train for passenger connectivity. It is also to be noted that the requirements of throughput for some video applications of FRMCS by far exceed the throughput capabilities of the dedicated railway spectrum at 1900 MHz which can be observed in Figure 2 and Figure 3. This can only be achieved by communication service providers (CSPs) using a mid-to-high band spectrum (for example, 200 MHz in the 3.5 GHz band). Hence, there is a definite need to combine CSP networks in conjunction with FRMCS operating in a 1900 MHz band, either as primary or complementary access. In the most straightforward deployment approach where a CSP network is the primary access, CSPs can offer both critical and non-critical network slices for the safety-critical use cases and passenger connectivity, respectively. On the other hand, a hybrid network approach, where CSP networks act as complementary access, enables the integration of railway infrastructure managers at various levels [8]. Therefore, due to the importance of CSP networks in providing railway services, some countries have decided that due to high CAPEX and OPEX against the dedicated railway networks, they will be relying primarily on CSP networks for FRMCS.

Cross-border synchronization and service continuity

Critical FRMCS applications have little tolerance for service interruption putting additional challenges on the network deployment at country borders which typically suffer from longer outages. There are several steps to addressing this, starting with time division duplexing (TDD) pattern alignment and the subsequent synchronization of cross-border networks, so that coverage at country borders can be as seamless as possible. An aligned TDD operation, where the same TDD pattern is used across borders, minimizes interference and maximizes the spectrum utilization. If differing TDD patterns are used, downlink transmissions colliding with the uplink transmissions need to be blanked to protect uplink transmissions in a region of about 10 km to 50 km depending on adjacent channel or co-channel operation, leading to a decreased downlink capacity of the radio access network in this region.

Beyond TDD alignment, the core networks, as well as the service layers on both sides of the border, must be configured and integrated in such a way that the users on the train have continuous service for the respective safety-critical applications [4]. This includes optimized handover procedures between the two radio access networks, session migration from one core network to the other, and user migration on the service layer. Also considering the shift of responsibility for applications from one country's rail infrastructure manager to another, the border crossing scenario is the eventual crux, to be tackled in FRMCS standardization, to realize a pan-European railway network. In addition, the fact that several devices on a train need to communicate through one or more user equipment (UE) for the respective applications, adds further to the complexity of border crossing scenarios. The challenge can be broken down into several building blocks, as illustrated in Figure 4. It is to be noted that alternative approaches are also under discussion that deviate from the classical roaming approaches.

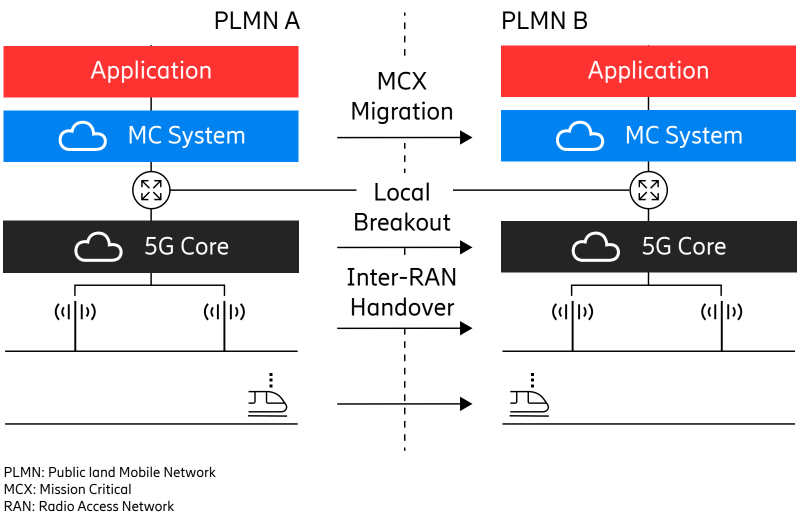

Figure 4. Border crossing requires several steps to set up optimal connectivity in the new country

Handing over to the visited radio access network (RAN) can be achieved with an N2-based inter NG-RAN handover, which involves moving the existing packet data unit (PDU) session to the target RAN, using the access and mobility function in the visited network. This optimized configuration reduces the handover interruption time to about 100 ms [6]. As a result, the target RAN will be used, but the PDU session will still be anchored in the old core network, and the IP address configuration of a UE will not be affected yet. This means that all user data will first be routed back to the home network, before breaking out of the core network and being routed to the destination.

Some applications require a more optimized user data path, with a local breakout of the PDU session in the visited network. By configuring a local breakout in the visited network for a corresponding PDU session, the home network will initiate that the PDU session is deleted and directly reactivated afterwards, that is, it will essentially trigger the UE to reconnect, leading to a user data path terminated at the local breakout in the visited network. Finally, for communicating with a local application in the visited country, mission critical service

(MCX) clients on the train need to be migrated to the MCX system in the visited country, which is still under standardization in 3GPP.

When the local breakout in the visited network is set up for the PDU session, a new IP address is assigned to the UE. While applications on the UE itself must be able to cope with this change, (for example, by reestablishing Layer 4 sessions, or using more advanced Layer 4 protocols like QUIC [9] or multipath TCP [10]), devices on the network behind the UE first need to know about this IP address change, or - when framed routes are used - also get a new IP address assigned that corresponds to the new network location in the visited network. With dynamic host configuration protocol (DHCP), IPv4 only offers a request-based dynamic IP assignment method, without an intrinsic method to push new or modified IP configurations to an IP host, in this case, a device in the onboard network of the train. IPv6, however, uses router advertisements to announce the presence of routers to IP hosts, which can also be used to advertise new IP addresses. MCX clients on the onboard network, being connected to the MCX System via framed routes through the 5G network, also require new IP addresses, which need to be assigned over the top of the 5G system (Figure 5).

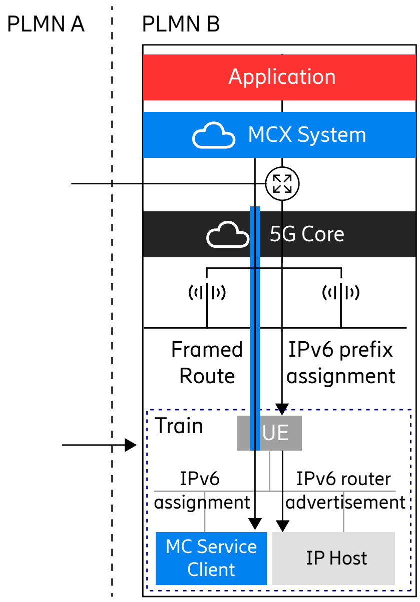

Figure 5. IPv6 allows for pushing IP configuration updates to IP hosts, which is especially useful for the dynamic connectivity situation in railways, including border crossing scenarios

While the mechanisms for this still need to be discussed and agreed upon, IPv6 offers a substantially larger toolbox, including not only push-based IP assignments, but also better multihoming and redirection support for the transition phase, multi-UE connectivity, and rail-specific corner cases.

Migration to FRMCS

UIC plans to make the first edition of the FRMCS ecosystem available for procurement by the first quarter of 2025. During migration, which may last until 2035, FRMCS will coexist with GSM-R resulting in the interoperability requirements on FRMCS systems. Therefore, it is believed that 5G network deployments should happen on a 1900 MHz dedicated spectrum and/or spectrum owned by CSPs which will serve as an overlay network to GSM-R operating at the 900MHz band. This will ease the migration of railway communication systems from GSM-R to FRMCS.

In order to enable FRMCS to keep up with the rapid development of connectivity technologies, FRMCS architecture is divided into three decoupled stratums: the applications, service, and transport stratums. This modular design enables FRMCS onboard systems on trains to support legacy and entirely new applications—possibly with diverse QoS requirements—using a variety of bearers simultaneously, referred to as bearer flexibility. Bearer flexibility is a useful feature when migrating existing onboard units, currently running over GSM-R, since these devices will also be able to operate over FRMCS radio through a suitable FRMCS gateway and adapter function, as detailed in [7].

Key takeaways

FRMCS is the successor of GSM-R systems, of which the main goal is to fully digitalize railway operations, support an increasing level of automated train operations, enable many new applications, and embrace the possibilities offered by 5G without creating a railway specific cellular network technology. 3GPP has specified many 5G features that not only meet the high reliability and/or low latency requirements of high-speed train scenarios but also provide the required system flexibility to support a diverse range of FRMCS applications.

Below, the three key takeaways of this white paper are highlighted:

1. Operating 5G NR at a 1900 MHz dedicated railway spectrum fulfills the performance requirement of safety-critical FRMCS applications requiring low to moderate throughput (that is, 0.1-20 Mbps), while using the 900 MHz band comes with coexistence issues with GSM-R and potential interference from the neighboring cellular bands. Therefore, 1900 MHz is a better choice than the 900 MHz band. For very high throughput demanding applications (30 Mbps and above on uplink), more spectrum is needed which can only be provided in a spectrum owned by CSPs. In light of this, Ericsson recommends the railway industry uses hybrid networks. A hybrid network approach will allow the railway industry to make use of 5G connectivity in both railway dedicated spectrum and CSP-owned spectrum for FRMCS applications.
2. Cross-border handover scenarios must be thoroughly studied, solved, and harmonized, to enable fluent pan-European railway operations. To this end, ETSI is working on several aspects that will jointly provide optimal coverage, smooth radio handovers, and seamless migration of backend connectivity, where IPv6 offers several advantages as compared to IPv4.
3. Lastly, 5G network deployments should happen on a 1900 MHz dedicated spectrum and/or spectrum owned by CSPs which will serve as an overlay network to GSM-R operating at the 900 MHz band. This will ease the migration of the railway communication system from GSM-R to FRMCS.

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Authors

Shehzad Ali Ashraf is a Master Researcher at Ericsson Research, having joined the company in 2013. He holds an MSc. in electrical engineering from RWTH Aachen University. Since joining Ericsson, he has been deeply involved in various internal and external research projects related to the development of 5G and 6G technologies. He has also served in 3GPP standardization and as a project manager of a research project looking into vertical industries like railways. Currently, he is acting as a technical area coordinator focusing on radio access technologies, which can enable new capabilities and ecosystems for cellular technologies.

Keerthi Kumar Nagalapur is a Senior Researcher at Ericsson Research, Gothenburg, Sweden. His current research activities focus on MIMO communications, and 5G NR for public safety and high-speed train communications. He holds a PhD in electrical engineering from Chalmers University of Technology, Gothenburg, Sweden.

Gabor Fodor works at Ericsson Research Radio in Kista, Sweden. He is also an adjunct professor at the KTH Royal Institute of Technology. He holds a PhD degree from Budapest University of Technology, a docent degree from KTH, and a DSc. degree from the Hungarian Academy of Sciences. He is currently serving as Chair of the IEEE Communication Society Emerging Technology initiative on full duplex and self-interference cancellation and as an editor of IEEE Transactions on Wireless Communications and IEEE Wireless Communications.

Christian Kuhlins is Strategic Product Manager for Cellular IoT RAN connectivity focusing on use case areas uncrewed aerial vehicles, railways, utilities, and healthcare at Ericsson. After completing his education in microelectronics at the University of Applied Science, Nürnberg, he joined Ericsson in 1998. Christian has worked on various technologies over the past 20 years and has been heavily involved in the early development of Bluetooth, WCDMA RAN and LTE RAN, holding various positions within R&D. He chaired the IoT Activity Group at the LTE SAE Trial Initiative (LSTI). As a Product Manager, Christian has worked with a variety of RAN products within Ericsson and is now a passionate evangelist of cellular IoT.

Bastian Cellarius-Toups graduated from RWTH Aachen University in 2015 with an MSc. in communications engineering and has been working at Ericsson Germany ever since. After working on media compression and delivery, LTE broadcast, and 5G communication for the automotive industry, he is currently a Senior Researcher at Ericsson in the field of end-to-end cellular communications systems for the railway sector. This includes 5G core and IP network design, higher layer protocols, architecture of mobile devices, inter-edge mobility, multiaccess, multipath, and border crossing optimizations, among other topics.

Stefano Sorrentino is Principal Researcher at Ericsson Research in Stockholm, Sweden, coordinating research activities on prioritized verticals and industries. He graduated from Politecnico di Milano and joined Ericsson in 2008. Since then, he has worked as a 3GPP RAN1 delegate and contributed to the creation of new 3GPP systems for public safety and for the automotive industry. He received the Inventor of the Year award in 2018, for his contributions to Ericsson's IPR portfolio. More recently, Stefano has been Chairman for the System Architecture group in the 5G Automotive Association, where he now acts as Ericsson's alternate board member.

David Rothbaum serves as Director of Business Development in the Mission Critical Networks organization within Ericsson. He is responsible for providing the railway industry with connectivity solutions using 4G and 5G for critical operational applications. He began his career at Nortel Networks where he held various senior engineering and managerial positions. At Ericsson, he has been involved in developing critical communications solutions for railways and serves as an Ericsson delegate in ETSI Railway Telecommunications, UNITEL, and ECC committees developing the FRMCS framework. David holds a BA Sc. degree in electrical engineering from the University of Toronto and an MSc. degree in management from Boston University.