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Internet of Things and the challenges for cross-border network slicing in 5G-based smart networks

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Internet of Things and the challenges for cross-border network slicing in 5G-based smart networks

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Final version

Abstract

The transition towards 5G-based smart network industries is concomitant with a fundamental change of the traditional physical infrastructures driven by digitalization which pervades all decision-relevant components of the infrastructure value chains. The goal of this paper is to develop a network economic foundation for 5G based network slicing based on a generalization of the concept of virtual networks combining a required sequence of virtual networks in order to fulfill the necessities of smart network industries. Whereas interoperability and interconnection between different virtual networks are not standardized significant standardization efforts via network slicing can be observed in particular from the perspective of end-to-end QoS guarantees. 5G-based big data use cases with cross-border challenges for network slicing, and the subsequent interoperability of virtual networks, enable tremendous potential for innovation in smart physical infrastructures. The 5G-based European Future Railway Mobile Communication System (FRMCS) and cross-border oriented, 5G-based connected, cooperative, and automated mobility applications (CCAM) are investigated with a large and open set of heterogeneous use cases begging for cross-border standardization of QoS-differentiated network slices.

1 Introduction

5G networks, with their fixed and mobile convergence and potential for large broadband capacity and ultra-low latency guarantees, represent an application-blind General-Purpose Technology (GPT), spurring changes in the communications and entertainment industries, as well as for a large and open set of Internet of Things (IoT)-based applications (Knieps, 2021). Considerable innovational potential evolves for use cases (“vertical industries”) pertaining to physical applications and services such as manufacturing, logistics, agriculture, e-health, and network industries (DotEcon & Axon, 2018; 5G PPP Technology Board & 5G IA Verticals Task Force, 2020; Global 5G, 5G PPP, 2021). IoT and the transition towards 5G-based smart network industries is concomitant with a fundamental change, driven by digitalization, in the traditional physical infrastructures that pervade all decision-relevant components of the infrastructure value chains (Atkinson, 2021). The innovation potential within markets of various smart physical network services is sharply increasing. 5G-enabled innovation results in disruptive challenges within the digitalized physical network infrastructure architectures and in an open set of innovative physical network services.

IoT-based use cases lead to advancements in the development of the complementary virtual side of smart vertical industries, under the heading of 5G-based end-to-end network slicing, combining 5G bandwidth capacities with other Information and Communications Technologies (ICT) such as cloud computing and big data centers. Network slicing is based on separate, independent end-to-end logical networks on the same 5G communication network infrastructure, ranging from user equipment to various mobile applications where each network slice has its own service-level agreement and objective requirements (3GPP TR 28.801, V 15.1.0, 2018; Rokui et al., 2020; ETSI TS 123 501, V 16.6.0, 2020).

The goal of this paper is to develop a network economic foundation for 5G-based network slicing driven by a generalization of the concept of virtual networks. The increasing dynamics of IoT-based use cases shift the focus onto the application-driven virtual networks, which combine the various dimensions – such as camera-based sensing, big data collection and processing, cloud computing (global and edge cloud) – with the all-IP bandwidth capacities, depending on the specific requirements of the use cases under consideration (Knieps, 2017). Since the governance and decision competence of each virtual network provider is limited by the geographical borders of its 5G based network, the end-to-end perspective of network slicing may involve the coordination problem of a sequence of virtual networks and thereby a multitude of 5G networks.

The paper is organized as follows: In Section 2 the 5G-driven dynamics of future smart network industries is characterized from the perspective of the Internet of Things (IoT) and subsequent use cases (verticals). The roles of QoS differentiation of 5G networks and subsequent network slicing and their relation to 5G-based virtual networks are analyzed. Standardization of network slicing is especially relevant due to interoperability and interconnection requirements between different virtual networks in order to guarantee end-to-end QoS requirements of 5G bandwidth capacities for a sequence of virtual networks. Of particular relevance are big data use cases with cross-border challenges for network slicing and subsequent interoperability of big data virtual networks along with large innovation potential in cross-border smart physical infrastructures. Important classes of use cases are considered in European railroad and highway systems with a need for standardization of network slices.

In Section 3 the evolution of the European Future Railway Mobile Communication System (FRMCS) is investigated. Digitalization of European railroads is driven by innovational complementarities along the whole value chain of railroad systems and has a tremendous impact on the standardization of cross-border network slices. FRMCS plays the role of an umbrella concept, with heterogeneous network slicing depending on the application use cases under consideration. An open set of innovative application services is enabled with QoS-differentiated network slicing. In particular, FRMCS roaming capabilities are required in order to ensure that railway operators are able to use the identical FRMCS equipment for their FRMCS users while roaming. A necessary condition for the operation of international trains for passenger or freight transportation across borders is that FRMCS users have access to the required QoS-guaranteed communication resources in all other FRMCS networks encountered (3GPP TR 22.889, V17.4.0, 2021). The provision of service continuity requires the ability to provide the same QoS, regardless of whether the FRMCS user is using the domestic FRMCS network or those in other regions.

Section 4 is devoted to 5G-based digitalization of European highways and heterogeneous, QoS-differentiated network slicing. Cross-border-oriented 5G-based cooperative connected, and automated mobility projects (CCAM) are analyzed with particular focus on the challenges of 5G cross-border corridors and concomitant standardization problems. The focus of the heterogeneous European cross-border-oriented trial projects is to implement many different use cases in order to enable innovative, vehicle-based applications by upgrading vehicles to smart vehicles based on the progress of 5G technology. The flexibility of 5G networks to provide very high throughput, together with guarantees of very low latency, enables innovations in traditional road safety applications. Furthermore, completely new areas of disruptive

innovation based on the ultra-low latency requirements of the tactile internet – such as cooperative networked self-driving vehicles on cross-border highways – have begun to emerge, as demonstrated by a multitude of use cases in cross-border situations (5G PPP, 2020).

Section 5 summarizes the conclusions, pointing out the problem-solving value of network slicing based on a generalization of virtual networks as a key driver for the evolution of smart network industries.

2 Network economics of 5G-based network slicing

Recently, the term “network slicing” has become increasingly popular in characterizing the combination of QoS-specified bandwidth capacity with other ICT dimensions – such as (camera-based) sensing, geolocational awareness, and big data processing in the central cloud or edge cloud – in order to fulfill the application-specific requirements of the use case under consideration from the end-to-end perspective and taking into account data protection regulations and cybersecurity (3GPP TR 28.801, V15.1.0, 2018; AdaptiveMobile Security, 2021; GSMA, 2021c; Rokui et al., 2020; 5G PPP, 2020, p. 8).

2.1 Network slicing from the perspective of 5G-based virtual networks

The network economic concept of virtual networks is related to the network engineering framework of network virtualization for future networks as developed by the ITU-T (2012, p. 2): “Network virtualization is a method that allows multiple virtual networks, called logically isolated network partitions (LINPs), to coexist in a single physical network.” From a network economic perspective, different governance problems arise: Network economic characteristics of virtual networks focus on the complementary role of traffic service providers and virtual network providers. The property rights and decision competency of traffic service providers are different from those of virtual network providers. Whereas the focus of traffic service providers is to offer QoS-differentiated bandwidth capacities for a large variety of possible applications, the entrepreneurial task of virtual network providers is to combine a specific QoS bandwidth capacity with other virtual resources (big data processing, sensor networks, geolocation services) in order to provide the required complementarity to specific physical applications (Knieps, 2017). The network slicing concept points to the interoperability and interconnection requirements of combining 5G-based virtual networks from the application-driven, end-to-end perspective whereby several virtual network providers may be involved.

Governance problems arise concerning the organization of the interaction between all-IP traffic service providers, virtual network service providers, and platform operators providing the physical network services. It is necessary to tailor the network slicing from the end-to-end perspective of the requirements of 5G-based smart network infrastructures.

2.2 The basic characteristics of network slicing

Whereas interoperability and interconnection between different virtual networks are tackled with complex coordination problems, large standardization benefits of network slicing can be observed in particular from the perspective of end-to-end QoS guarantees of 5G bandwidth capacities for a sequence of virtual networks. The focus of this paper is on 5G-based big data use cases with cross-border challenges for network slicing and subsequent interoperability of virtual networks in order to exploit the large innovation potentials in cross-border smart physical infrastructures. Whereas there are many alternatives for entrepreneurial management and the orchestration of network slicing regarding the network resources and the actors involved, the organizational end-to-end responsibility has to be in the hands of the network slice provider, based on the coordinated services of the involved virtual network providers, in order to fulfill the requirements of the IoT application. Security and privacy are considered particularly important for the 5G networks of the future. Privacy and security requirements for virtual networks are further elaborated and specified within broader privacy and security requirements laid down in network slicing standardization documents (ETSI TS 123 501, V16.6.0, 2020; ETSI TS 133 501, V16.3.0, 2020; GSMA, 2020). Organizational governance problems arise due to different possible contractual relationships between the parties involved.

Network slicing is a dynamic approach with an open set of innovative solutions depending on the IoT applications under consideration. Multiple actors may have an active role in network slicing. Network operators in their role as traffic service providers design, build, and operate 5G networks with a variety of QoS bandwidth guarantees. A network slice can be tailored based on specific requirements laid out in a Service Level Agreement (SLA), agreed to by network slice customers and network slice providers (GSMA, 2020, p. 9; GSMA, 2021a, GSMA, 2021b).

Network slicing, with its combination of end-to-end QoS bandwidth guarantee and other network resources such as processing power and storage, provides a logical separate end-to-end QoS guarantee within a 5G network, thus enabling the creation of new IoT applications and services, parts of which can be implemented over different network slices (5G PPP

Technology Board & 5G IA Verticals Task Force, 2020, pp. 20, 58). Network slicing combines customizable QoS bandwidth capacity with complementary ICT components – such as edge computing, precise positioning, and cellular V2X communications – that will operate in demanding environments such as geographical cross-border areas (5G PPP, 2020, p. 8; GSMA, 2021a, p. 9).

To implement network slicing, a proper combination of network resources is required, including radio spectrum frequencies, QoS bandwidth capacity, and data processing and storage capacities (GSMA, 2021b, p. 11). A variety of network slice types may be implemented according to the IoT application requirements. Resource requirements vary depending on the necessities of different types of network slices along different dimensions. These may include region specification (country-wide, regional, local, international), QoS parameters of bandwidth capacity, such as, sensitivity to delay variations, downlink throughput per network slice, and maximum supported packet size. Active QoS traffic management includes the implementation of priority levels indicating the most pressing concerns in scheduling resources among QoS flows. Performance monitoring has many faces. Thus, network operators and network slice customers are able to monitor key quality indicators measuring the end-to-end service performance. Performance criteria may entail session and service continuity, as well as whether a network slice can be used by a device simultaneously with other classes of network slices (GSMA, 2021a, p. 9).

2.3 The standardization of heterogeneous QoS-differentiated network slices

Interoperability and interconnection between different virtual networks are not standardized. In contrast, large standardization efforts can be observed with regard to network slicing, particularly from the perspective of end-to-end QoS guarantees of bandwidth resources for a sequence of virtual networks. Network slicing is standardized for purposes of interoperability and interconnection supporting the roaming use cases. The goal of this standardization of slice/service types is to enable end-to-end interoperability for slicing among different Public Land Mobile Networks (PLMNs), depending on the specific requirements of the use case under consideration (ETSI TS 123 501, V16.6.0, 2020, pp. 197f.). Nevertheless, the required network resources for edge computing, location accuracy services, etc. may also vary between different use cases, even if they belong to the same Slice/Service type (SST). Therefore, the introduction of standardized network slices generalizes the potentials of big data virtual networks, enabling interoperability and interconnection among virtual networks.

With the focus on 5G QoS bandwidth characteristics, four basic types of network slices have been standardized by the ETSI 3rd Generation Partnership Project (3GPP)¹ based on the IMT (International Mobile Telecommunications) triangle (ETSI TS 123 501, V16.6.0, 2020, p.198, Table 5.15.2.2-1): Slice/Service Type 1, enabling the handling of 5G enhanced mobile broadband (eMBB); Slice/Service Type 2, enabling ultra-reliable low-latency communications (URLIC); Slice/Service Type 3, enabling massive IoT (MIoT); and Slice/Service Type 4 (extending the IMT triangle), enabling V2X services.

34 attributes are defined to characterize what a customer might expect from network slicing (GSMA, 2021a, pp.12-63, based on ETSI TS 123 501, V15.3.0, 2018), particularly in terms of availability, area of service, delay tolerance, throughput per network slice, and slice quality of service parameters. These attributes define all the QoS-relevant parameters supported by the network slice. For some of these parameters, standard values have been defined by pre-selecting a 5G QoS identifier (5QI). For customized 5QIs parameter values must be selected. Of particular relevance for the end-to-end QoS guarantees of network slices is the packet delay budget, defining an upper bound for the time that a packet may be delayed; packet error rate, defining an upper bound for the IP packets not successfully delivered from the sender to the receiver; and the maximum packet loss rate (GSMA, 2021a, Table 43, p. 46). Standardized 5QI to QoS characteristics mapping can be implemented for a variety of applications (use cases) such as intelligent transport systems, augmented reality electricity distribution, etc. (ETSI TS 123 501, V.16.6.0, 2020, Table 5.7.4-1, pp. 147-151). Furthermore, network slice-specific authentication and authorization are required.

Standardization of network slicing is characterized as an open evolutionary search process, one that leaves ample entrepreneurial degrees of freedom regarding the design of network slices depending on the requirements of the application use cases involved.

¹3GPP is a worldwide standardization platform for global mobile communication systems with the seven regional telecommunication associations involved in standardization procedures as primary members (Association of Radio Industries and Business /ARIB, Alliance for Telecommunications Industry Solutions/AT&T, China Communications Standards Association/ CCSA, European Telecommunications Standards Institute/ETSI, Telecommunications Standards Development Society/TSDSI, Telecommunications Technology Association/TTA, Telecommunications Technology Committee/TTC). In addition, industry alliances also participate in the 3GPP (Gu et al., 2019, pp. 27f.).

2.4 Heterogeneous e-privacy and security requirements

Security and privacy requirements are an important dimension of logically isolated network partitions (LINPs) coexisting in a single physical communication network. Security and privacy issues should be considered during planning and designing of network virtualization solutions, including the security and privacy requirements of both users and service providers. All virtual resources for building an LNP – such as cloud computing services, geolocation services, etc. – should fulfill the privacy and security requirements. Since LINPs are isolated and individually managed, the security problems of any individual LNP should not spread to other LINPs (ITU-T, 2012, pp. 6, 10-12). From the perspective of network economic governance, privacy and security are important dimensions of each virtual network. The responsibility for privacy and security on the virtual side of IoT applications should be placed in the hands of the provider of the virtual networks (Knieps, 2019, p. 179).

Security and privacy are also considered particularly important for the 5G networks of the future (Brake, 2016, p. 5). End-to-end privacy and security requirements for network slices and the concomitant sequence of virtual networks are further elaborated and specified in network slicing standardization documents (AdaptiveMobile Security, 2021; ETSI TS 133 501, V16.3.0, 2020; GSMA, 2021c, pp. 32-41). Through interconnection and roaming, the Public Land Mobile Network (PLMN) is exposed to other networks, thus revealing the importance of a secure network design that isolates all parts of the network that need not be reached from the outside, secures all entry points into the networks at the edge, deploys secure communication between PLMNs, and introduces, applies, and maintains security procedures. With 5G, the 3GPP introduces new security controls that allow secure inter-operator communications to be implemented. A necessary requirement for a secure network is that the design guarantees that the impact of a failure or an attack is limited as it cannot spread to other parts of the network (AdaptiveMobile Security, 2021, p. 31). A disaggregated approach to security mechanisms within 5G network slicing has been proposed to differentiate between high-assurance security enablers that are present in all slices and, in addition, application-specific security mechanisms for each slice. Heterogeneous security requirements exist among the different network slices, depending on the use case under consideration. Safety-critical applications, such as smart train applications or networked vehicle applications, have particularly high safety requirements.

The areas of security and privacy are particularly focused on new security controls and secure inter-operator communications with a network design guaranteeing that the impact of a failure

or attack is limited and unable to spread to other parts of the network. These concerns are addressed with a particular emphasis on 5G roaming security architecture (GSMA, 2021c, pp. 32-41).

3. Digitalization of European railroads and 5G-based network slicing

In order to analyze the peculiarities of network slicing for smart railroads, the evolution of the European Future Railway Mobile Communication System (FRMCS) is investigated. Digitalization of European railroads is driven by innovational complementarities along the whole value chain of railroad systems and their tremendous impact on the standardization of cross-border network slices.

3.1 The transition to the 5G-based Future Railway Mobile Communication System (FRMCS)

Traditionally, the European Rail Traffic Management System (ERTMS) has consisted of two subsystems with the following characteristics: the European Train Control System (ETCS), a train control standard with a complementary interaction of in-cab equipment (onboard unit) and trackside equipment (balise), as well as the Global System for Mobile Communications-Railways (GSM-R). GSM-R is a narrowband mobile communication system with additional specifications for train communication requirements. It uses exclusive frequency bands to facilitate communication between the train, devices beside the track, and the traffic control centers.

In 2016, ERTMS Level 3 was defined in a Commission Regulation² specifying that communication regarding train position and train integrity is to be conducted directly between the train and the radio block center, thus diminishing the formerly central role of balise-based fixed block signaling systems (Furness et al., 2017; De Grandis, 2020). In the meantime, a shift from the widely implemented ERTMS Level 2 (based on the narrowband GPS-R) to broadband ERTMS Level 3 is considered a “game changer”, greatly increasing track capacity and precluding the need for large investments in trackside train detection equipment or additional lines. As a means of enabling increased traffic and greater track capacity without building additional tracks, providing real-time multimedia information, and ensuring passenger safety,

² Commission Regulation (EU) 2016/919 of 27. May, 2016, OJ L 158/1

the transition from narrowband GSM-R to broadband communication systems seems unavoidable.

Meanwhile, the transition towards a 5G-based Future Railway Mobile Communication System (FRMCS) has gained high priority within European infrastructure policy focused on motorways, national roads, and railways in the context of trans-European transport networks (European Commission, 2016, p. 7; European Union Agency for Railways, 2018).³ The transition towards smart railroad networks requires a shift from the conventional narrowband GSM-R towards broadband QoS-differentiated communication networks (Fraga-Lamas et al, 2017; International Union of Railways (UIC), 2019; Nokia, 2019; Pieriegud, 2018). In particular, high-speed railways have strict requirements for quality of service (QoS) parameters such as transmission delay, data rate, and bit error rate (He et al., 2016, pp. 49f.).

3.2 Network slicing for a large variety of 5G-based FRMCS use cases

The shift from a railroad-specific GSM-R communication system to 5G-based FRMCS with an open set of 5G-based use cases is strongly rooted in the concept of network slicing. 5G-based network slicing is considered key for future rail operations (ETSI, TR 103 459, V1.1.1, 2019, p. 25).

There arises a large diversity of communication QoS requirements for different FRMCS applications. Three category types of use cases in the context of FRMCS are classified, differentiating between critical, performance, and business use cases. Examples of critical use cases are applications for train control services, railway emergency communication, automatic train protection (ATP) support by the FRMCS system, trackside maintenance, warning system communication-related use cases, public emergency call-related use cases, automatic train operation data communication, as well as monitoring and control of critical infrastructure-related use cases. Examples of performance use cases are applications intended for improving the performance of railway operation, in-train communication between staff and train passengers, and communication within train stations. Business use cases entail billing information, applications that provide wireless Internet for passengers on the train, and entertainment

³ Although there is a common understanding that the narrowband GSM-R system is outdated, the transition investment plans vary between different European countries. In particular, the question arises of whether a transition to 4G and onwards to 5G could also be recommended, combined with protecting investments whilst allowing for future evolutions (de Grandis, 2020).

communications (3GPP TR 22.889, V.17.4.0, 2021; International Union of Railways (UIC), 2019, in particular Appendix A pp. 451-453).

Depending on the necessities of the use cases under consideration, a bandwidth capacity with a specific spectrum, frequency, and QoS guarantee must be combined with other ICT components such as cloud computing (central or edge), camera-based sensor networks, and geopositioning services. Another important dimension of network slicing for safety-critical rail applications is cyber security, as elaborated in FRMCS end-to-end security (ETSI TR 103 459, 2019, pp. 33-35).

From the perspective of 5G-based virtual networks, different organizational governance alternatives can be identified, which are network economically oriented (Knieps, 2017). The entrepreneurial combination of the required ICT components is chosen, resulting in the desired big data virtual network for the rail use case under consideration. Different use cases may require common inputs, such as radio frequencies, and at the same time use different ICT components such as cloud computing, sensor networks, etc. Rail operations may be based on a rail-dedicated spectrum, whereas business applications may be provided by a public mobile network operator using a licensed spectrum. Multiple train companies may also base their operations on a common communication system utilizing individual slice per train company.

Different use cases for network slicing are identified, which are characterized by different organizational scenarios. Depending on the requirements of the different use cases involved, a heterogeneous division of labor between mobile network operators (MNO) and railway operators may evolve with the concomitant governance problems of train operator platforms (ETSI TR 103 459, 2019, p. 25).

Train operator platforms offer the potential to shift network intelligence from the railroad tracks to the trains and 5G-based train traffic control systems, thereby strongly increasing railroad track capacities without the requirement to build new tracks. The shift from a fixed block system to a 5G communication-based moving block system – with the benefit of increasing track capacities – only becomes possible due to QoS guarantees of very low latency and related safety improvements (3GPP TR 22.889, V17.4.0, 2021, pp. 174-180). Competition on the tracks among different train companies is enabled by allocating different network slices to different rail operators, such that several rail operators can share a common communication system with each user utilizing an individual slice. Several categories of applications belonging to one rail operator can be provided by heterogeneous network slices differentiating between safety-critical, performance, and business categories (3GPP TR 22.889, V.17 4.0, 2021,

pp. 232-234). The topical relevance and potential of network slicing in future European railway systems can be summarized as follows: “Network slicing allows the operator to provide customized networks. For example, there can be different requirements on functionality (e.g., priority, charging, policy control, security, and mobility), differences in performance requirements (e.g., latency, mobility, availability, reliability, and data rates) or they can serve only specific users ... ” (3GPP TR 22.889, V.17 4.0, 2021, p. 234).

3.3 Cross-border challenges for FRMCS network slicing

A necessary condition for the operation of international trains for passenger or freight transportation across borders is that FRMCS users have access to the required QoS-guaranteed communication resources across the entire range of FRMCS networks, whether traveling from one’s home FRMCS network to a visited FRMC network (and vice versa), or from one visited FRMC network to another (3GPP TR 22.889, V17.4.0, 2021, pp. 235-239). The provision of service continuity and the ability to provide the same QoS is crucial, regardless of whether FRMCS users are using their home FRMCS network or an FRMCS network elsewhere. In particular, FRMCS roaming capabilities are required to ensure that railway operators can use a single piece of FRMCS equipment for their users while roaming. Detailed requirements for user equipment for network slicing when roaming are specified in GSMA (2021c), pp. 20-23.

There exists a diversity of communication requirements for the large variety of use cases with the highest QoS requirements (ultra-low latency guarantees) for critical applications.

FRMCS/5G support for railway applications is based on standardized network slicing in order to identify slices unambiguous across countries (or even worldwide) (ETSI TR 103 459, V1.1, 2019, Table 3, pp. 21-30). Particular focus is given to border crossing scenarios in ETSI TR 103 459, V 1.2.1, 2020, pp.40-49. The policy and charging control framework dealing with flow-based charging for network usage, including charging control, is considered in ETSI TS 123 503, V16.5.0, (2020).

The geographical dimensions of network slicing in railroad networks entail local/regional, domestic, and cross-border similarities and differences within the European railroad systems. A multitude of cross-border challenges for FRMCS network slicing arise. A necessary condition for the operation of international trains for passenger or freight transportation across borders is that FRMCS users have access to the required, QoS-guaranteed communication resources across all FRMCS networks. The provision of service continuity and the ability to provide the same QoS are essential, regardless of whether FRMCS users are using their home FRMCS

network or an FRMCS network farther afield. FRMCS plays the role of an umbrella concept, with heterogeneous network slicing depending on the application use cases under consideration. Varied and innovative application services are enabled by QoS-differentiated network slicing. In particular, FRMCS roaming capabilities are required to ensure that railway operators are able to use a single piece of FRMCS equipment for their FRMCS users while roaming (3GPP TR 22.889, V17.4.0, 2021, pp. 235-241).

4 Digitalization of European highways and 5G-based network slicing

The focus in the following section is on cross-border-oriented 5G-based cooperative, connected and automated mobility projects (CCAM). Developing a 5G-based CCAM ecosystem in Europe is rooted in innovational complementarities between digitalized vehicles, digitalized road traffic control, and digitalized road infrastructure in order to enable vehicle-to-vehicle communication (V2V), vehicle-to-infrastructure communication (V2I), and infrastructure-to-infrastructure communication (I2I).

4.1 Innovational complementarities on digitalized European highways and 5G cross-border corridors

Physical road traffic applications and complementary ICT networks were originally based on a special-purpose networked vehicle architecture. A large number of use cases focusing on active road safety and cooperative traffic efficiency have been developed, although fully automated driving has not yet been considered (ETSI TR 102 638, 2009). The shift from a special-purpose communication architecture to the all-IP-based multipurpose communication networks was initiated by the ITU-T International Telecommunication Union (ITU-T, 2011) and the Internet Engineering Task Force (IETF) (Knieps, 2019, pp. 173f.). From the IoT perspective, the physical side and the complementary virtual side are to be differentiated. The focus of the heterogeneous European cross-border-oriented trial projects is to implement a large number of different use cases in order to enable innovative, vehicle-based applications by upgrading vehicles to smart vehicles based on the innovational progress of 5G technology.

Initiated by the 5G Pan-European Trials Road Map Version 4.0 (5G IA, 2018), a first phase of cross-border projects started in November 2018, consisting of 5GGroCo, 5G-CARMEN, and 5G MOBIX. A second phase of cross-border projects started in September 2020, consisting of

5G MED, 5G Blueprint, and 5G Routes.⁴ The first phase was primarily focused on highway projects and their cross-border challenges: between Metz, Merzig, and Luxembourg (5G CRoCo), Porto-Vigo between Spain and Portugal (5G MOBIX), and Bologna-Munich via the Brenner Pass (5G CARMEN). The ongoing second phase is enlarging intermodal perspectives by including road and rail 5G network infrastructure, including maritime routes and ports (IDATE, 2021, pp. 44 f.).

Within 5G-CARMEN, a multi-tenant platform for 5G-enabled Cooperative, Connected and Automated Mobility (CCAM) services is provided, combining vehicle information with precise positioning and traffic information. Examples are situational awareness concerning the surrounding environment as a result of 5G infrastructure, traffic safety improvements, facilitated emergency vehicles, green driving use cases to reduce air pollution via a dynamic speed limit; and video streaming applications within national boundaries and across-borders. Within 5G MOBIX, a multi-tenant platform for 5G-enabled CCAM services is provided within the Cooperative, Connected and Automated Mobility (CCAM) project, which combines vehicle information with precise positioning and traffic information (5G MOBIX, 2019, 2021). Enhanced situational awareness regarding the surrounding environment is made possible by 5G infrastructure. Similar to the 5G-CARMEN project, this improves traffic safety, facilitates the public services provided by emergency vehicles, enables green driving use cases to reduce air pollution by means of a dynamic speed limit, and enables video streaming applications within national boundaries and across-border.

The transition to 5G-based CCAM requires the building of 5G networks and network slicing on the virtual side, as well as the path-dependent upgrading of the physical roadside infrastructure. The role of innovational complementarities also requires that the vehicles be upgraded. The role of 5G networks along transport corridors points to the particular relevance of cross-border interoperability issues, in particular regional borders, national border conditions, and cross-border conditions (5G PPP, 2020, p. 2).

A particular challenge of the future governance of 5G-enabled CCAM ecosystems is the interaction among the traditionally separated actors involved, which may manifest either on the physical side – such as automobile manufacturers and road operators – or on the ICT-based virtual side, such as cloud providers (central cloud, edge cloud), camera-based sensor and locational geopositioning service providers, and new players providing disruptive innovative

⁴ A map of the geographical dimensions of these cross-border projects is provided in IDATE 2021, p. 44; see also ACEA, CEDR, GSMA & 5GAA (2020, Annex 1, p. 16).

services by building new shared mobility driverless operator platforms (5G IA, 2020, pp. 7-9; 5G PPP, 2020, pp. 6-8).

4.2 Cooperative, Connected and Automated Mobility (CCAM) use cases and a variety of network slices

The flexibility of 5G networks to provide very high bandwidth capacities, together with guarantees of very low latency, enables innovations in traditional road-safety applications, such as anticipated cooperative collision avoidance. Furthermore, completely new areas of disruptive innovation, such as cooperative networked self-driving vehicles on cross-border highways, have begun to emerge, as demonstrated within the 5G CroCo use cases in cross-border situations (5G PPP, 2020, pp. 10-13). Connected vehicles will be enabled to exchange safety-critical information in real time with very low latency, as well as other less QoS-demanding use cases that represent a broad range of digital services for drivers and passengers. Of particular relevance is the local sharing of video-based data. By means of network slicing, the end-to-end requirements of different use cases can be guaranteed. By combining QoS bandwidth capacities with other ICT – such as cloud computing (central cloud and edge cloud), locational positioning services, and privacy and safety requirements – big data virtual networks for a variety of different use cases can evolve. A question arises regarding the role of standardization of QoS bandwidth guarantees and further standardization requirements for network slicing. Challenges for cross-border regulatory frameworks arise, as well: “the most challenging environment in this case become the national borders between countries where interoperability and smooth service migration between the neighbouring networks, infrastructures and applications need to be guaranteed” (5G PPP, 2020, p. 9).

4.3 5G-enabled CCAM in cross-border scenarios and heterogeneity of cross-border network slices

5G-enabled CCAM in cross-border scenarios is configured within the 5G-CARMEN, 5G CRoCo, and 5G MOBIX trial projects. Of particular relevance are the innovational complementarities between the physical and virtual sides of 5G-enabled CCAM applications. On the physical side, driverless vehicle software must be programmed to respect local traffic laws and understanding safety-related messages is necessary to avoid dangerous traffic conditions. On the virtual side, the legal framework, regulation, and governance of mobile networks must

be adapted. Europe-wide, cross-border solutions require a seamless handover across MNOs to enable CCAM services such that a vehicle remains connected to the gateway of the previous MNO. Network slicing entails 5G communication technology combined with other components such as sensors and positioning systems. Several challenges and possible solutions for the effective provision of cross-border 5G-based CCAM services are identified, pointing to the relevance of cellular coverage and radio access, standardization of network reselection and concomitant QoS prediction, security and standardization of roaming and data routing, cross-border data management via cross-border message brokers, and the role of security and privacy regulatory compliance (5G PPP, 2020, Table 3, p. 42). Challenges of cross-border solutions are the necessity of a seamless handover of edge computing data to assure some kind of “managed latency” between MEC (Multi-Access Mobile) edge computing/cloud, session/service continuity across MNOs, predictions regarding expected QoS changes after the handover from one MNO to another, ensuring service continuity, and efficient driving behavior. A particular role of cross-border message brokers is considered among road authorities, road operators, service providers, and connected vehicles. The future challenges will require collaboration of the different parties involved to fulfill the end-to-end latency guarantee requirements. Innovative application services, such as networked driverless vehicles, require digitalization investments in upgrading roadside infrastructure with sensors and positioning systems, investments in new upgraded vehicles, and investments in operator platforms. End-to-end (E2E) QoS with network slicing is grounded in different standards based on 3GPP Release 15 (3GPP TR 28.801, V 15.1.0, 2018) for MNOs and data center technologies for interoperable multiple logical networks of shared communications infrastructure. Of particular relevance is the role of roaming agreements to support network slicing with the multitude of Generic Slice Templates leaving ample room for entrepreneurial flexibility regarding the design of network slicing (GSMA, 2021a, pp. 11-63).

5 Conclusions

The focus of this paper is on big data use cases with cross-border challenges for network slicing and subsequent interoperability of virtual networks and large innovation potentials in cross-border smart physical infrastructures. 5G-based European Future Railway Mobile Communication System (FRMCS) applications, as well as cross-border-oriented 5G-based cooperative, connected and automated mobility applications (CCAM), are investigated with a large and open set of heterogeneous use cases. Although the physical side of digitalized European

railroads and highways is characterized by many differences, the transition to general-purpose 5G networks and concomitant network slicing shows many similarities. Using network slicing, various types of applications, such as low-latency remote driving applications and platooning applications, may be supported at the same time despite their different virtual network characteristics – e.g., different frequency bands, heterogeneous throughput requirements, different latency tolerances, and heterogeneous security requirements (5G PPP 2020, p. 8). The process of cross-border 5G-based network slicing within smart European railroads and highways is characterized by important similarities and common elements: a transition from special-purpose communication networks to general-purpose 5G networks, heterogeneity of applications requiring 5G-based network slicing with safety-critical and non-safety-critical physical applications, and the need for cross-border end-to-end guaranteed network slicing. The focus of network slicing is on end-to end QoS, including the feedback of cloud computing processing times on the latency budget of the network orchestrator (ACEA, CEDR, GSMA & 5GAA, 2020, p. 13).

Business models for cross-border environments involve different actors that participate in the value chain, such as automotive suppliers, telecom equipment vendors, mobile network operators, and original equipment manufacturers (5G PPP, 2020, pp. 30-48). Business models have to consider the interaction of different players – including traffic service operators, network infrastructure providers, vehicle manufacturers, 5G communication network providers, and 5G-based network slice providers – depending on the heterogeneous requirements of the final customers for the smart physical network services.

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