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Data-driven sector coupling in 5G-based smart networks

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Abstract

5G attains the role of a GPT for an open set of downstream IoT applications in various network industries and within the app economy more generally. Traditionally, sector coupling has been a rather narrow concept focusing on the horizontal synergies of urban system integration in terms of transport, energy, and waste systems, or else the creation of new intermodal markets. The transition toward 5G has fundamentally changed the framing of sector coupling in network industries by underscoring the relevance of differentiating between horizontal and vertical sector coupling. Due to the fixed mobile convergence and the large open set of complementary use cases, 5G has taken on the characteristics of a generalized purpose technology (GPT) in its role as the enabler of a large variety of smart network applications. Due to this vertical relationship, characterized by pervasiveness and innovational complementarities between upstream 5G networks and downstream application sectors, vertical sector coupling between the provider of an upstream GPT and different downstream application industries has acquired particular relevance. In contrast to horizontal sector coupling among different application sectors, the driver of vertical sector coupling is that each of the heterogeneous application sectors requires a critical input from the upstream 5G network provider and combines this with its own downstream technology. Of particular relevance for vertical sector coupling are the innovational complementarities between upstream GPT and downstream application sectors. The focus on vertical sector coupling also has important policy implications. Although the evolution of 5G networks strongly depends on the entrepreneurial, market-driven activities of broadband network operators and application service providers, the future of 5G as a GPT is heavily contingent on the role of frequency management authorities and European regulatory policy with regard to data privacy and security regulations.

Keywords

Sector coupling, Internet of Things (IoT), 5G, generalized purpose technology, big data, innovational complementarities

JEL classifications: L51, L92, L96, R41

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Introduction

The next evolution of mobile technology, the fifth generation (5G), is characterized by fixed and mobile convergence with fundamental changes to the network architecture—particularly small cell deployment, fiber backhaul networks for small cells or, alternatively, wireless backhaul technologies. Moreover, the spectrum scarcity problem, together with harmonization requirements, is increasing. Path dependency of fixed infrastructure should be taken into account in the process of network densification, such that existing fixed infrastructure can supply backhaul for mobile infrastructures to some extent (within geographic, economic, technical, and regulatory limits) (European Union, 2018, p. 2; ITU-T, 2018). 5G takes into account stringent requirements for throughput capacity (enhanced broadband) and critical communications (low latency, high reliability). Furthermore, 5G enables the creation of a massive Internet of Things (IoT), e.g. a large number of connections with low power and low cost (ITU-R, 2015, figure 2, p. 12). The evolution of 5G has made it a general-purpose technology (GPT) applicable to a large set of IoT applications such as networked driverless vehicles, inspection drones, security cameras, and sensors for industrial or agricultural applications. 5G also enables the Tactile Internet, with ultra-low latency requirements and big data applications with mobile functionality, as well as many other applications with less demanding QoS (Quality of Service) requirements for data packet transmission due to higher latency tolerance and low power consumption (e.g. Brake, 2016, pp. 2–6; Knieps, 2019a, p. 174).

The transition toward 5G networks is not only a challenge for the communications and entertainment industries, but is also a major driver for the transition toward smart networks and is a general feature of the app economy. 5G has attained the role of a GPT for an open set of downstream IoT applications in various network industries and within the app economy at large. In this way, it is fundamentally changing the future role of sector coupling. Whereas sector coupling has traditionally been a rather narrow concept focusing on the horizontal synergies of urban system integration in terms of transport energy and waste systems or the creation of new intermodal markets, 5G general-purpose technology has become the driver for vertical interrelation (coupling) in an open set of smart downstream application industries, thereby enlarging the scope of downstream horizontal sector coupling applications. The goal of this paper is to investigate the major drivers and necessities of 5G-based vertical sector coupling from the perspective of the downstream application requirements. We examine spectrum allocation, QoS differentiation of data packet transmission, and the creation of big data value chains as important dimensions for the design of 5G-based big data virtual networks necessary to fulfill the requirements of the IoT applications.

5G networks fundamentally change the framing of sector coupling in network industries, underscoring the relevance of differentiating between horizontal and vertical sector coupling. Due to the fixed mobile convergence and the large open set of complementary use cases, 5G has taken on the characteristics of a GPT in its role as the enabler of a large variety of smart network applications. Due to this vertical relationship, characterized by pervasiveness and innovational complementarities between upstream 5G networks and downstream application sectors, vertical sector coupling between the provider of an upstream GPT and different downstream application industries has gained in importance. In contrast to horizontal sector coupling among different application sectors (e.g. mobility-as-a-service markets integrating rail and road transport services), the driver of vertical sector coupling is that each of the heterogeneous application sectors requires a critical input from the upstream 5G network provider and combines this with its own downstream technology. Of particular relevance are the innovational complementarities between upstream GPT and downstream application sectors. Innovations in the upstream GPT increase the productivity of

R&D in downstream application markets and, in turn, these downstream developments facilitate further improvements to the GPT. This basic interrelation between GPT-based upstream semiconductors and different downstream sectors (hearing aids, radio TVs, etc.) has been analyzed by Bresnahan and Trajtenberg (1995), who focus on the role of innovational complementarities and related vertical externalities between upstream GPT and downstream application sectors within a stylized framework. The quality of upstream GPT has been characterized by these authors as a one-dimensional, homogeneous parameter (density of transistors on a chip), such that each downstream application sector relies on this input and combines it with its own downstream technology. Considering the character of 5G as GPT, the upstream technology is characterized as multidimensional bandwidth capacity with different quality of service (QoS) parameters (jitter, delay, packet loss). All-IP broadband networks with active traffic management function as GPT for application services. Innovation may be stimulated by positive feedback effects between upstream 5G and downstream application use cases. Innovational complementarities arise between upstream GPT (application blind) and downstream application sectors (use cases). The traffic service provider chooses a particular QoS traffic architecture with concomitant price and bandwidth investment decisions depending on the demand of application providers for heterogeneous QoS guarantees (Bauer & Knieps, 2018, p. 183; Knieps & Bauer, 2016, p. 75).

5G has the character of an envelope design concept with large potential for heterogeneous implementations, depending on the 5G big data virtual networks required for the IoT applications. Vertical sector coupling with 5G networks is relevant for all application sectors or use cases, irrespective of whether these applications could also be realized within 4G/LTE or 3G mobile networks. This is because 5G is a GPT application blind for an open set of IoT applications, and the 5G resources (frequencies, bandwidth capacities, QoS architectures) are to be allocated to a heterogeneous set of IoT applications combined with the required data value chains. It follows that vertical coupling between 5G and application sectors must take into account both sides, with upstream 5G all-IP network capacities tailored to the specific requirements of downstream application sectors. Depending on the downstream application sector requirements, the pricing and investment decisions of 5G network providers vary. It follows that active, interactive sector coupling is driven by adequate price and investment signals at the upstream level.

With 5G, a new generation of GPT has evolved, enabling an innovative space of use cases and applications, data-driven sector coupling based on 5G virtual networks and 5G applications driven by IoT. IoT has both a physical side, comprising applications, and complementary virtual sides, resulting in the problem solution competence of big data virtual networks. While the physical infrastructures vary strongly between different network industries, the complementary information and communication technologies (ICT) are based on sensors, real-time and location-aware communication, and data processing. The governance problem between all-IP traffic service providers and application-driven virtual network providers thus assumes particular relevance (Knieps, 2017a, 2019a). Important dimensions of 5G big data-based virtual networks are 5G frequency combined with other dimensions such as QoS-differentiated broadband networks. Furthermore, data value chains based on data collection within camera-based sensor networks, big data processing and aggregation, and location-sensitive data information gathering are important inputs for 5G-based big data virtual networks. Since 5G-based big data virtual networks are application driven, the required resources within the different dimensions and the requisite local/regional footprint vary according to the necessities of the applications.

The paper is organized as follows: The second section is devoted to 5G spectrum allocation as an important driver of vertical sector coupling. In order to fulfill the requirements of a GPT as

precondition for a large variety of IoT applications, the future evolution of 5G networks and subsequent 5G-based big data virtual networks strongly depends on the spectrum management solutions of the frequency management authorities. The spectrum scarcity problem, together with harmonization requirements, is increasing and the allocation and standardization of the 5G radio spectrum is becoming increasingly relevant. 5G networks require a fundamental shift of spectrum allocation principles from special-purpose frequencies toward general-purpose frequencies. The third section is devoted to big data value chains. It is necessary to tailor big data value chains from the perspective of the requirements of 5G-based virtual networks, taking into account data protection regulations and cybersecurity. Data-driven sector coupling requires an understanding of the potential of big data value chains in Europe and their applicability for IoT and 5G-based virtual networks. Integrating data value chains into big data virtual networks raises entrepreneurial decision problems. The governance of heterogeneous operator platforms requires a market-driven, entrepreneurial choice of combining big data value chains with the different dimensions of big data virtual networks.

The fourth section is devoted to several use cases that illustrate the enlarging scope of data-driven IoT applications. We demonstrate data-driven innovations and the resulting potential for big data-driven horizontal sector coupling in various smart network industries. Potentials of 5G-based horizontal sector coupling vary at the downstream level. Examples are mobility-as-a-service markets and intelligent transportation systems, big data-driven congestion management based on shared mobility data, and big data-driven sector coupling in microgrids. Moreover, the opportunities afforded by 5G-based native applications, such as Tactile Internet, are illustrated via the example of big data-driven networked driverless vehicle platforms, highlighting the complementary role of the highest QoS standards of broadband traffic service providers and mobile edge computing. The fifth section summarizes the conclusions.

Spectrum allocation for future 5G-based virtual networks

Frequencies in the context of 5G big data virtual networks (Knieps, 2019a) raise issues regarding the heterogeneity of frequency requirements regarding local footprint (geographical flexibility), time windows, and the minimal bandwidth required depending on the type of IoT application in question. Frequency usage rights may be allocated nationwide, regionally, or locally. In the European context, Germany and the United Kingdom are pioneers in allocating exclusive frequency usage rights locally, thereby enabling the flexible setup of independent, locally dedicated 5G networks (also known as private 5G campus networks). Since frequencies are an essential input for (wireless) 5G campus networks, they are of particular relevance for a large variety of local 5G-based IoT applications and use cases, such as industry 4.0 (smart manufacturing), agriculture, forestry applications, intralogistics transport systems, asset tracking, augmented maintenance, safety monitoring, and remote control (Ericsson, 2020; Jurva et al., 2020, Sörries & Nett, 2019).

From special-purpose frequency allocation toward uncoupled frequency allocation

Spectrum allocation requirements within 5G networks are becoming more demanding due to significant performance improvements over 4G in the form of extremely high data rates, very low latency, greatly increased capacity, etc. Heterogeneity of spectrum depends on the frequency of electromagnetic waves (in Hz) varying between the radio, microwave, infrared, and visible light regions of the spectrum. Whereas data rates increase with higher frequency spectrum, spatial coverage and mobile use are superior in lower frequency ranges (Singh et al., 2019, p. 5/40,

figure 5). Nevertheless, the question arises as to what extent different frequency bands are economic substitutes for a considered class of applications.

Within 5G networks there is an increasing trend of turning away from special-purpose frequency allocation toward application-blind, unbundled, flexible allocation. Whereas historically, radio frequencies were strongly coupled to specific types of service (e.g. broadband, radio stations, voice communications), the transition toward all-IP-based next-generation networks (NGN) has hastened the movement toward the unbundled, flexible provision of frequencies (Gomez et al., 2018, pp. 6 f.).

The heterogeneity of spectrum bands depends on application requirements, but there is a significant degree of flexibility. The geographical scope of spectrum harmonization and common standards depends on the class of applications. 5G-based cloud gaming or video streaming requires worldwide common QoS standards (or at least worldwide interoperability requirements) similar to the classical ITU standards for voice quality. In contrast, the typical footprint for IoT applications within smart sustainable cities, intelligent transportation systems, and smart energy networks is either local, regional, countrywide, or spanning an entire continent. The question then arises: Why should this create a coordination and compatibility issue? Differentiation potentials seem to exist between worldwide compatibility requirements (e.g. to exhaust economies of scale in complementary equipment) and footprint-based virtual networks required to operate a subway within a city or a smart road system within a region.

Market-based, uncoupled spectrum allocation and its limits

The allocation problem of scarce radio frequencies, which describes the issue of interference between operators on a single frequency or interference between operators on adjacent frequencies, has been analyzed by Coase (1959), with a focus on the importance of the definition of property rights and the subsequent role of market transactions. The key to solving this issue is the legal delimitation of the rights of operators to transmit signals which interfere or might potentially interfere with those of others. After such a legal delimitation of rights has been implemented, the rearrangement of rights through market transactions can evolve. It should not be assumed that the socially optimal level of interference is zero if the benefits of interference exceed the harm it produces. Since the transaction costs of such rearrangements may be significant, however, the most efficient delimitation of rights might not be attained. It might even be the case that the original delimitation of rights is maintained, even though others would be more efficient (Coase, 1959, pp. 27 f.).

From the network economics perspective, there arise questions regarding the capabilities and limits of market-based solutions to the interference problem (Coase, 1959; Hazlett et al., 2011). From the economist's point of view the question arises whether there are particular limitations to market-based approaches or additional systematic problems with frequency allocation due to critical infrastructures and the safety requirements of operators of essential services.[1] Critical infrastructures of topical relevance to regulatory frameworks—such as

1. Directive (EU) 2016/1148 of the European Parliament and of the Council of 6 July 2016 concerning measures for a high common level of security of network and information systems across the Union OJ L 194/1, 19.7.2016. (See in particular Annex 2 focusing on energy [electricity, oil, gas], transportation [air transport, rail transport, water transport, road transport], banking, financial market infrastructures, and the health sector.)

railroads, urban transport, and road systems—must be analyzed in order to tackle these complex issues.

The specification of the economic role of interferences requires technical/engineering knowledge regarding the nature of interference, such as diminishing the quality level of communication (noise) (Shannon, 1948). The complexities of interference depend on the number of parties involved, the frequency bands in question, intra- vs. interband interference, etc. Different application services on a given frequency band may have varying sensitivities regarding a specific form of interference. Interference may have several dimensions: not only noise in communications due to a spillover in frequencies, but also power interference such that physical health may be negatively impacted (ITU-T, 2019).

Scarcity and interference as drivers for uncoupled spectrum sharing solutions

If the primary allocation of spectrum bands by technical committees is taken as a given, the degrees of freedom and flexibility for bilateral and multilateral spectrum sharing among spectrum users within the technical regulations can nevertheless be identified (CEPT/ECC, 2018). The role of priority rules for different safety-relevant applications can be critically evaluated through the lens of network economics. Economic incentives to deal with the degrees of freedom in the secondary spectrum markets may be created through different types of cooperation and sharing agreements, as well as side payments. When designing alternative incentive schemes, the basic principle of opportunity cost demands consideration of the role of technical side constraints in order to avoid safety-critical interferences. The question arises of whether it is possible to improve the efficiency of spectrum usage (taking into account the safety requirements) through secondary trading between the parties involved under application of dynamic spectrum sharing and spectrum pooling. The role of new players in the market, such as newcomers with critical infrastructure/essential services as well as newcomers from other non-critical services, can be analyzed (Lehr & Jesuale, 2009).

The focus is on sharing solutions shifting from separated sub-bands with different priorities for the involved parties toward market-driven sharing based on opportunity costs of utilization of spectrum (the value of the alternative use). Technological progress regarding spectrum usage is changing opportunity costs for spectrum allocation mechanisms, thus creating innovative forms of sharing (dynamic spectrum sharing, spectrum pooling). The role of innovational complementarities should not be neglected. Innovations in the complementary dimensions may occur, e.g. big data and complementary investments.

Data-driven sector coupling, 5G and a European strategy for data

Particular focus is placed on the pivotal role of big data-driven innovations and concomitant data-driven sector coupling. Big data and the organization of data value chains is gaining increasing attention in network industries, with special focus on adaptive real-time and location-based data collection by means of ubiquitous sensor networks, as well as remote data storage and processing centers in the cloud (ITU-T, 2014a). Important application fields are intelligent transportation systems (OECD/ITF, 2015, 2016), smart sustainable cities (Al Nuami et al., 2015; ITU-T, 2015a; OECD, 2015), and smart renewable energy systems (ITU-T, 2015b; Knieps, 2017b). Driverless vehicle platforms provide highly interactive (cooperative) networked/automated

vehicles with the support of high-volume, location-critical big data processing (edge cloud) (Knieps, 2019a; OECD/ITF, 2015).

Digitalization and the transition toward a European data economy

European reform proposals on the future role of data, algorithms for machine learning, and subsequent artificial intelligence (AI) are gaining increasing attention (European Commission, 2020a, 2020b, 2020c). The transition from conventional network industries toward smart networks, and more generally toward the IoT within the app economy, is strongly based on big data-driven innovations, resulting in a large expansion of data volume as well as increasing heterogeneity of the data.[2] Challenges arise in terms of building trust for data-driven innovations within the IoT of the future (OECD, 2015). The General Data Protection Regulation (GDPR),[3] which has been in effect since May 2018 (repealing the Directive of 1995), aims at the protection of natural persons with regard to the processing of personal data and at the free movement of such data across the European Union, avoiding fragmentation in the implementation of data protection. An additional regulation regarding the protection of personal data if data processing of European institutions is involved was passed in 2018.[4] The goal of recent European legislation concerning open data and the re-use of public sector information has been advanced by the Open Data Directive.[5] The European Union Open Data Portal[6,7] contains numerous examples of companies benefiting from access to open data for heterogeneous use cases in areas such as intelligent transportation services, smart sustainable cities, smart energy networks, e-health, public safety, and smart agriculture in different European countries (European Commission, 2020a, pp. 6–8). Public sector information with a particular focus on real-time, location-aware applications is open to everyone. For example, in all areas where precise geopositioning is of particular importance (e.g. aviation, networked driving, navigation in smart cities) geopositioning services are provided by EGNOS (European Geostationary Navigation Overlay Service), without competition over use of positioning data (Knieps, 2019b, pp. 26 f.).

The entrepreneurial role in creating data value chains consisting of privately held, non-personal data is gaining increasing relevance in the growing IoT and related field of artificial intelligence-based machine learning. The process of data collection via sensors, aggregation of data, data

2. Big Data has been defined as "[a] paradigm for enabling the collection, storage, management, analysis and visualization, potentially under real-time constraints, of extensive datasets with heterogeneous characteristics" (ITU-T, 2015c, p. 2). Over the last several decades, rapid technological progress in IP-based sensing and communication technologies, strongly enhanced storage capacity, and increased computing speed for the collection and exploitation of large datasets (big data) have become important drivers for the change of conventional network industries into smart networks.
3. Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016 on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation), OJ L 119/1, 4.5.2016.
4. Regulation (EU) 2018/1725 of the European Parliament and of the Council of 23 October 2018 on the protection of natural persons with regard to the processing of personal data by the Union institutions, bodies, offices and agencies and on the free movement of such data, and repealing Regulation (EC) No. 45/2001 and Decision No. 12347/2002/EC.
5. Directive (EU) 2019/1024 of the European Parliament and of the Council of 20 June 2019 on open data and the re-use of public sector information OJ L 172/56, 26.6.2019.
6. https://www.europeandataportal.eu/en/using-data/use-cases.
7. Towards a European strategy on business-to-government data sharing for the public interest, Final report prepared by the High-Level Expert Group on Business-to-Government Data Sharing, 19. February 2020, http://www.eoc.org.cy/en/index.php?id=1395,footnote147, p.93.

processing, data analysis, use and re-use of data should not be hampered by data localization requirements by Member States' authorities. The goal of a recent regulation with particular focus on data processing is to enable the free flow of privately held, non-personal data in the European Union such that data localization requirements by Member States shall be prohibited unless they are justified on the grounds of public security.[8] Access to open data and to public sector information—as well as the free movement of privately held, non-personal data without data localization requirements—is gaining relevance for the entrepreneurial design of data value chains. It is expected that the growing role of the IoT will dramatically change the processing and analysis of big data from centralized computing in the cloud to edge computing in the neighborhood of the users. European data strategies focus on the interaction between the government to business (G2B), business to government (B2G), and Business to Business (B2B) sectors, as well as the requirements of IoT for the data economy (European Commission, 2020a).

Data value chains from the perspective of 5G-based big data virtual networks

IoT is characterized by the complementary roles of physical networks and virtual networks providing the required network intelligence for smart network infrastructures and smart network services (Knieps, 2017a, 2019b). 5G and concomitant 5G-based big data virtual networks also fulfill the demanding strong QoS requirements with regard to bandwidth capacities of the Tactile Internet. 5G is a general-purpose technology for a large and open set of IoT applications with heterogeneous ICT requirements entailing heterogeneous Quality of Service (QoS) requirements in terms of bandwidth capacities, heterogeneous sensor networks, heterogeneous (big) data processing capacities and heterogeneous security requirements.

Data-driven sector coupling requires an understanding of the potential of big data value chains in Europe and their applicability for IoT and 5G-based virtual networks. Integrating data value chains into big data virtual networks raises entrepreneurial decision problems. The ITU-triangle characterizes 5G as a combination of high requirements for throughput capacity (enhanced broadband), critical communications (low latency, high reliability), and requirements of massive IoT (large number of connections with low power, low cost). Necessities for complementary combinations of the three dimensions—at least to some extent—arise such that throughput is not a substitute for QoS traffic requirements (European Commission, 2016a, 2016b; ITU-R, 2015; ITU-T, 2018).

The real total amount of data generated, processed, and stored by ICT and other sensors is increasing dramatically, although the concrete measurement is rather speculative (OECD, 2015, p. 20). More important in our context is the heterogeneity of data value chains depending on the requirements for specific IoT applications. Heterogeneous requirements arise regarding data generation, data aggregation, data sharing, data processing, central cloud computing, edge cloud, or local cloud. Also, of particular relevance is the QoS in data transmission. Cloud computing-based big data capabilities entail data collection, data pre-processing, data storage, data analytics, data visualization, data management as well as data security and protection (ITU-T, 2015c, pp. 14–16). Several governance problems arise: The technical literature on big data and cloud computing characterizes the setup of alternative cloud service models and alternative cloud deployment

8. Regulation (EU) 2018/1807 of the European Parliament and of the Council of 14 November 2018 on a framework for the free flow of non-personal data in the European Union, OJ L 303/59, 28.11.2018.

models (public cloud, private cloud, or hybrid cloud) without providing recommendations regarding the allocation of the decision competencies among the different parties involved (cloud service customers, cloud service providers) (ITU-T, 2014a, pp. 5–8).

However, to fulfill the requirements of IoT applications (networked vehicle applications, shared mobility service, microgrid, etc.), it is important that the virtual network providers have the entrepreneurial decision competencies necessary to design the big data value chains according to the requirements of the IoT applications, combining QoS-differentiated bandwidth capacities with the different complementary dimensions of virtual networks such as sensor networks, geo-positioning services, and the division of labor between central cloud and edge cloud. Governance problems also include the organization of the interaction between all-IP traffic service providers, virtual network service providers, and platform operators providing the physical network services (Knieps, 2019a, p. 176 f.; 2019b, pp. 23 f.).

From the perspective of big data virtual networks required for complementary physical network services, data value chains should reflect the necessities of the different dimensions of virtual networks such as big data analysis for sensor compression and strict positioning standards. QoS differentiation requirements of data packet transmission required by heterogeneous applications include the extremely low latency tolerance of the Tactile Internet shifting big data processing from the cloud to the edge cloud (Fettweis, 2014, p. 68; ITU-T, 2014b, pp. 8 f.). Incentives for the re-use or sharing of data are context-dependent based on the requirements of big data virtual networks and operator platforms for IoT applications. The resources required for 5G-based big data virtual network services are contingent not only on the data processing value chain but also on the QoS requirements of data packet transmission based on the QoS-differentiated bandwidth capacities, which all-IP traffic service providers are able to guarantee. The economic incentives of traffic service providers for price and QoS differentiation for a hierarchy of QoS-guaranteed traffic classes with heterogeneous parameter values regarding latency, jitter, and packet loss within a Generalized DiffServ traffic architecture can be derived based on the opportunity costs of the different traffic classes (Knieps, 2017a; Knieps & Stocker, 2016).

Big data-driven horizontal sector coupling in smart network industries

The potential of 5G-based horizontal sector coupling varies at the downstream level depending on the underlying fields of applications. Examples are mobility-as-a-service markets and intelligent transportation systems, big data-driven congestion management based on shared mobility data, and big data-driven sector coupling in microgrids. Moreover, the opportunities afforded by 5G-based native applications, such as Tactile Internet, are illustrated via the example of big data-driven networked driverless vehicle platforms.

Mobility-as-a-service markets and intelligent transportation systems

The growing relevance of sector coupling in urban transport is characterized by the transition of various conventional intramodal transportation markets toward intermodal shared mobility markets. Borderlines are becoming blurred between traditional intramodal transportation markets for scheduled public transit services by rail and bus and on-demand services with flexible time scheduling and routes. An evolving multiplicity of combinations of shared mobility services provides a substitute for private car trips. Such services include taxis, car rentals, carsharing, minibuses, buses, and high-capacity public transit via train, subway, or tram.

In order for app-based operator platforms to coordinate and organize the on-demand provision of mobility services in real time, location-based data are required (Knieps, 2018; OECD/ITF, 2016). Virtual networks for shared mobility services are necessary and complement the changing markets for physical transportation services. Different forms of sector coupling with heterogeneous virtual networks for shared mobility services arise based on the required combination of virtual networks, such as mobile real-time communication, global geopositioning services, and sensor-based data generation organized by app-based, data-driven operator platforms.

Complementary innovations arise between big data applications and sector coupling: The increasing potential of intelligent traffic information systems—such as the real-time distribution of information regarding road conditions, weather, accidents, traffic flows, traffic volume predictions, and route navigation—are based on ICT innovations such as global positioning systems (e.g. Galileo, EGNOS, GPS), broadband communication based on QoS-differentiated bandwidth capacities, and big data processing within the central cloud or edge cloud. Designers of transportation systems are currently focusing on data-based congestion management, traffic security systems, and environmental impact-based passenger information systems (Kemp et al., 2015; Knieps, 2019a, p. 175 f.).

Tremendous potential for the smart use of roads can be realized through real-time and location-based road user charges in accordance with the principles of congestion pricing. A rapid decrease in the transaction costs as a result of real-time and location-based congestion pricing is based on the technological progress in ICT that enables innovative traffic toll collection systems such as vehicular remote tolling, including a passenger monitoring system, without compromising the protection of personal data. Using demand-responsive road pricing to charge for the use of roads—with prices differentiated by route, location, time of day, and day of the week—is considered an important instrument for tackling congestion problems by reducing total vehicle trips, shortening trip distances, and shifting some vehicle trips from peak to off-peak periods (OECD/ITF, 2019). Within cities, there exist additional relevant factors influencing the individual choice of car ownership, such as parking fees and the integration of land-use and transport planning. A GPS-based road user charge system could also serve as a platform for other applications, such as automatic payments for on-street parking, and provide valuable information from onboard systems transmitting anonymized travel data to traffic managers and planners (Atkinson, 2019, pp. 7–9; OECD/ITF, 2018, pp. 20–23). Of particular relevance for the modal split within cities is the organization of shared mobility and complementary public infrastructures (e.g. drop-off and pick-up points at public transport stations), together with the integration of shared services as feeders to public transport (OECD/ITF, 2020, p. 9).

Big data-driven congestion management based on shared mobility data

Potential for sector coupling in intelligent transportation systems emerges when ride-sourcing companies collect anonymized real-time and location-based data and use them for active traffic management. Aggregated anonymized user data are gathered via shared mobility services, coupling data from mobility apps with an open traffic platform converting GPS data into travel times corresponding to road segments. Vehicle-based GPS data substitute for the installation of fixed-location roadside sensor equipment and therefore, a single cloud-based traffic management application can be applied across a large number of cities without additional effort. The open traffic platform links average traffic speed calculations to road segments, deriving real-time congestion

data. Peak hour analysis from the open traffic platform allows observers to determine weekday peak and non-peak travel patterns (World Bank, 2015).

Data value chains entail the collection, storage, processing, and dissemination of data. Anonymized smartphone data generated by a large number of trips operated via taxi or ride-sourcing platforms enable the setup of "open traffic" global platforms with big data processing capabilities for anonymous positioning of vehicles and smartphones, providing information on traffic speeds and traffic patterns on specific road segments. Starting with a collaboration between World Bank's Big Data Challenge Innovation Grant and Grab Taxi, an on-demand taxi service generating GPS data in countries the World Bank supports, an important goal has been peak-hour traffic analysis along key streets in selected Asian cities (World Bank, 2015). In the meantime, several ridesharing companies and navigation service companies have formed a partnership with the World Bank and jointly founded the Open Traffic Partnership platform to build a global architecture for sharing anonymized traffic data. The Open Traffic Partnership is a multipurpose platform aimed at supporting intelligent transport systems and efforts such as traffic signal timing plans, public transit provision, emergency traffic management, travel demand management, and roadway infrastructure requirements (OECD/ITF, 2016, pp. 29–33).[9]

The Waze App platform, a navigation system for smartphones, enables the sharing of real-time, location-based traffic data consisting of navigation information and user-submitted travel times and route details. Location-dependent information is provided over a mobile telephone network via a community-driven GPS navigation app, which is free to download and use. App-based sharing of publicly available, real-time traffic information is organized via the Waze App platform. In the context of its "Connected Citizens Program,"[10] Waze provides a citizen-government data exchange platform to partner cities, granting those cities access to its data in real time. This enables city authorities to identify congestion based on the analysis of users' GPS data. The goal of this public-private partnership is to improve the quality of the Waze App platform by receiving local road sensor data, publicly available information on local incidents, and road closure reports. The benefit for the partner cities is the ability to utilize Waze data on the Waze App platform, thereby receiving better information on current road conditions (OECD/ITF, 2016, p. 32).

Sector coupling within microgrid operator platforms

The shift from conventional to smart (high-voltage) transmission and (medium-voltage) distribution grids enables data-driven network operation based on real-time and locational node-based status of capacity usage. An upgrade of network intelligence is required based on innovations in metering, sensors, real-time interactive machine-to-machine communication, and remote control (Fang et al., 2012). Microgrids are located at the edge of the electricity grids. On the physical side, microgrids combine the low-voltage generation and consumption of electricity with a particular focus on renewable energy, coupling customer-tailored energy generation and storage with energy consumption.

The complementary virtual aspects of microgrids provide the required ICT components within innovative home network architectures, coupling the broadband capacities for prosumage sensor

9. The World Bank, feature story, "Open Traffic Data to Revolutionize Transport," December 19, 2016, http://www.worldbank.org/en/news/feature/2016/12/19/open-traffic-data-to-revolutionize.
10. For more information on the Waze Connected Citizens Program see https://wiki.waze.com/wiki/Connected_Citizens_Program.

networks with communication and entertainment applications (ITU-T, 2016). Top-down value chains with generation, high-voltage transmission networks, medium-voltage distribution networks, and low-voltage local consumption networks are increasingly being replaced by bottom-up renewable energy generation and consumption (prosumage) at a low-voltage level. The aggregation and balancing of real-time measured generation or consumption of the neighboring prosumers within a microgrid is organized by the microgrid platform operator. The import/export of electricity from/to the wholesale market is based on injection or extraction fees to be paid at the microgrid node located at the medium-voltage distribution grid. Whereas within microgrids the location of generation/consumption does not matter, disaggregated real-time and location-based nodal pricing is relevant in the medium-voltage distribution network, reflecting the node-specific costs of network access (Knieps, 2017b).

Big data-driven networked driverless vehicle platforms

Important innovations in 5G networks are driven by mobile edge computing. The focus is on IoT applications, where ultra-low latency is required. As an import class of use cases for mobile edge computing, connected vehicles and moving IoT devices are considered, requiring the devices to connect to the 5G network, moving across different cells with mobility and a guarantee of session continuity. This becomes relevant not only for road vehicles, but also for trains, drones, and other moving IoT devices (Sabella et al., 2016).

For the IoT applications of networked driverless vehicle platforms, the highly interactive sharing of anonymized, camera-based sensor data with ultra-high position accuracy, as well as guarantees of ultra-low latency, is required. Shifting the function of driver responsibility to the networked driverless vehicle platform entails high volumes of data, thus requiring big data pre-processing and compact data by means of large-scale computation within the edge cloud. The division of labor between central cloud computation and edge computing is of pivotal relevance in the context of networked driverless vehicle platforms. A shift from the central cloud toward the edge cloud yields the benefits of lower latency and bandwidth consumption (Chang et al., 2014, p. 346). Due to the high latency sensitivity of 5G-based big data virtual networks for networked vehicles, the local sharing and processing of camera-based sensor data within the edge cloud is of utmost relevance for the operation of driverless vehicle platforms. For Tactile Internet applications, such as networked driverless vehicles, the highest quality of bandwidth available would not be sufficient to guarantee the required ultra-low latency. Therefore, a shift toward the edge cloud is absolutely essential (Knieps, 2019a, pp. 175–179).

Conclusions

The 5G-driven IoT poses disruptive challenges to traditional network industries, enabling IoT applications for physical network services based on real-time, adaptive, and location-sensitive data. There is an open and ever-expanding set of physical IoT applications. Different 5G-based big data virtual networks, which are complementary to heterogeneous IoT application services, are based on the quality of service (QoS) requirements of all-IP broadband communication networks and related 5G spectrum allocations, sensor networks, geolocational services, and data processing. Important application areas are intelligent transportation systems, networked driverless vehicle applications along with smart energy systems enabling mobility-as-a-service markets, the coupling of intermodal transportation services, and microgrids coupling the local generation and

consumption of energy. Although data value chains are pivotal in developing IoT applications, the entrepreneurial governance problems within IoT require both physical and complementary virtual networks, together enabling adaptive, real-time, and location-differentiated network configurations for smart network applications.

Outputs from different sectors may converge into large competitive markets, e.g. mobility-as-a-service markets combining road and rail transport. Beyond the potential synergies of sector coupling between different applications (horizontal coupling), the potentials and requirements of vertical sector coupling are to be considered. The preconditions and possibilities of vertical sector coupling are based on the characteristics of 5G as a GPT that enables a large variety of smart network applications such that each of the heterogeneous applications requires a critical input from the upstream GPT industry and then combines this with its own downstream technology. From this arrangement, there arise new, innovative forms of sector coupling in smart network industries, enabled by 5G networks and concomitant data value chains. Of particular relevance are innovational complementarities between upstream 5G networks and downstream IoT applications with the entrepreneurial flexibility to combine the requirements of 5G with the necessities of downstream applications. It follows that vertical coupling between 5G and application sectors has to consider both sides, with upstream 5G all-IP network capacities tailored to the specific requirements of downstream application sectors.

Heterogeneous 5G usage scenarios are illustrated within the ITU-triangle, comprising applications such as smart cities, smart homes, industrial automation, and networked driverless vehicles (ITU-R, 2015, figure 2, p. 12). A variety of heterogeneous 5G-based use cases—e.g. in the automotive, media and entertainment, manufacturing, logistics, agriculture, energy and utilities, and healthcare sectors—are considered especially relevant for the future. Moreover, the potentials of 5G-based local networks (e.g. campus networks) are evolving, with increasing applicability to a large variety of use cases. It may be expected that the vast and unexhausted innovation potential of 5G-based use cases will also contribute expanding the possibilities of horizontal sector coupling within 5G-based IoT applications.

The focus on vertical sector coupling also has important policy implications. Although the evolution of 5G networks strongly depends on the entrepreneurial, market-driven activities of broadband network operators and application service providers, the future of 5G as a GPT is heavily contingent on the role of frequency management authorities and European regulatory policy with regard to data privacy and security regulations.

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