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Towards 5G: An Empirical Evaluation of Software-Defined End-to-End Network Slicing

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***Abstract*—Emerging systems such as the Internet of Things (IoT), Smart Grids (SGs), Industry 4.0, and Vehicle-to-Everything (V2X) impose a diverging set of requirements on underlying Information and Communication Technology (ICT) topologies. This relates to performance indicators including network delay, data rate, reliability as well as security. To meet these criteria, 5G aims to provide network slices, i.e., virtually independent architectures on top of a single, unified communication infrastructure. In this context, Software-Defined Networking (SDN) and Network Function Virtualization (NFV) have been identified as key technologies for implementing such a solution. This work utilizes these ingredients in conjunction for providing isolated end-to-end slices, from wireline cloud servers over the Software-Defined Radio (SDR)-based Long Term Evolution (LTE) Radio Access Network (RAN) down to individual User Equipments (UEs). Thereby, a prototypical 5G end-to-end slicing solution is designed and implemented. The system enables independent management of each slice by either its respective owner or the ICT infrastructure operator. Also, resources are allocated dynamically to slice tenants in order of their priority. A comprehensive empirical evaluation based on real-world traffic patterns, such as Floating Car Data (FCD), is given. Hence, compliance with Service Level Agreements (SLAs) - crucial to stable operation of e.g., SGs - is demonstrated for up- and downlink traffic flows.**

I. Introduction

Emerging use cases such as Smart Grid (SG) or Vehicle-to-Everything (V2X) communication impose challenging, diverging requirements on ICT. Thus, dedicated networks are desirable to fulfill their heterogeneous demands, typically associated with high costs and long deployment cycles. 5G aims to address this by instantiating multiple virtual topologies on a single, shared physical (i.e., substrate) communication infrastructure. These so-called network slices are tasked to meet demands of diverse tenants and use cases including Ultra-Reliable Low Latency Communication (uRLLC), Massive Machine Type Communication (mMTC), and Enhanced Mobile Broadband (eMBB), as depicted by Figure 1. However, no technical solution has yet been standardized. For evolving LTE towards 5G, we propose a novel end-to-end network slicing solution. RAN resources are shared among the created overlay networks through slice-aware scheduling. Core Network (CN) slicing is implemented with Network Function Virtualization (NFV) and Software-Defined Networking (SDN). The latter abstracts the control plane, i.e., the decision making process (e.g., routing), from the data plane that handles physical data packet forwarding. Hence, a centralized SDN controller software running on Commercial Off-The-Shelf (COTS) servers is created. It supports functionality upgrades without changes in hardware, as required by traditional networks. Also, the ICT infrastructure can be adapted flexibly to application demands via a Northbound Application Programming Interface (API). In this work, we present a Management and Orchestration (MANO) controller for slices creation, which are each managed by their own controller. Thus, tenants can control slices as if operating a fully owned network. NFV shifts functionalities such as load balancing or intrusion detection from integrated hardware to software components, i.e., Virtual Network Functions (VNFs). By deploying our per slice SDN controllers as such VNFs, virtual end-to-end topologies can be created on demand. A performance evaluation is conducted with real-world traffic patterns. We focus on the provisioning of service guarantees, i.e., Quality of Service (QoS) parameters such as delays and data rates as well as slice isolation. This is demonstrated in scenarios with dynamic resource allocation, according to slice/service priority, in up- and downlink across RAN and wireline CN. The paper is structured as follows: First, Section II gives an overview of related work. Next, we introduce the proposed 5G end-to-end network slicing concept in Section III. Its components in the RAN as well as in the SDN and NFV driven wireline 5G CN are detailed. Section IV provides a description of the test setup employed for the outlined, use case centric evaluation scenarios. Results gained by measurements conducted in this context are discussed in Section V, with a specific focus on QoS. Finally, Section VI summarizes our findings and gives an outlook on future work.

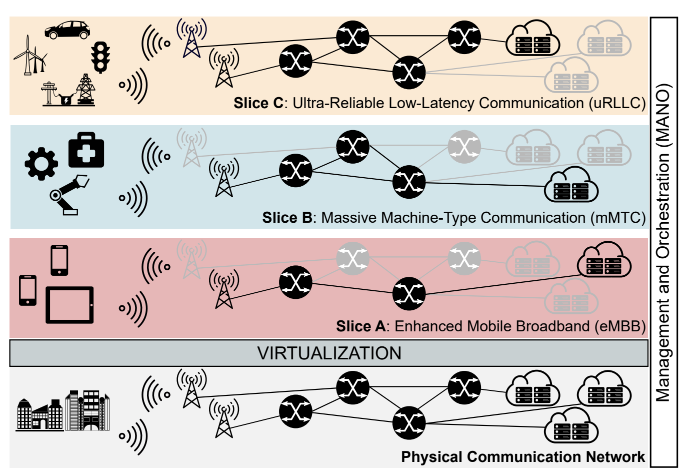

Figure 1: High-Level 5G Network Slicing Architecture

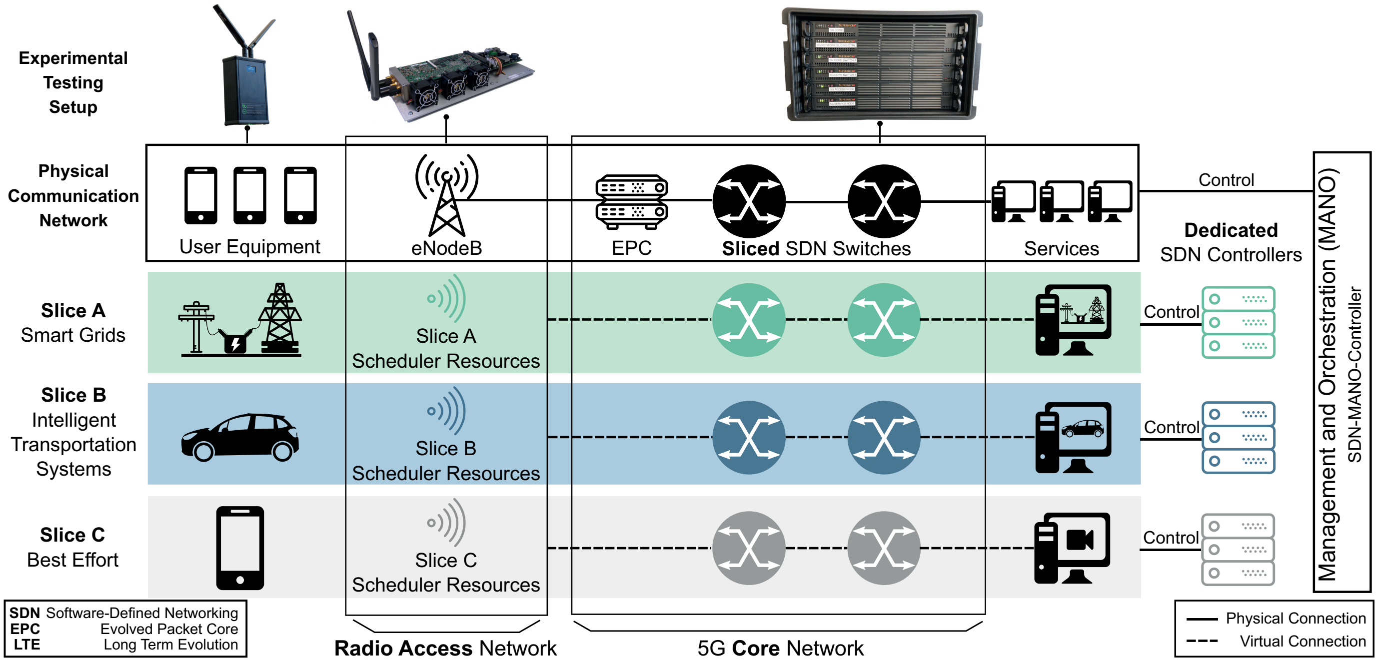

Figure 2: Architecture of the Developed Network Slicing System and Evaluation Scenario

II. Related Work

End-to-end network slicing is a crucial ingredient of 5G, as outlined by a technical report of the 3rd Generation Partnership Project (3GPP) [1]. It focuses on concepts regarding slice MANO. Prior 3GPP releases contain precursor technologies such as the Dedicated Core Networks (DECOR) (rel. 13) [2] and Enhancements for Dedicated Core Networks (eDECOR) (rel. 14) [3] features. These enable the assignment of different core networks, each with specific features and properties to diverse user types. Another concept is provided by the Next Generation Mobile Networks (NGMN) Alliance. There, a layered architecture, required entities and their relationships are detailed on an abstract level [4]. In the following, we focus on studies most relevant to the presented approach. A detailed survey on end-to-end network slicing in LTE and 5G, including standardization activities, is given in [5]. The authors of [6] describe RAN slicing based on LTE and IEEE 802.11, including challenges and potential solutions. A simulative investigation is given by [7]. Other works center on slicing of the core and wireline networks in general. Surveys highlighting the conceptual aspects of network slicing and the significance of SDN as well as NFV for its realization are given by [8], [9], [10], [11], and [12]. Theoretical and algorithmic perspectives are examined in [13], [14], [15], and in [16], [17] as well as [18], respectively. Meanwhile, prototypical evaluations often employ the OpenFlow (OF) proxy FlowVisor [19]. Such works span from limited QoS extensions [20] to management [21] and security aspects [22]. Solutions based on OpenDaylight controllers [23] are studied in [24] and [25].

In contrast to the studies outlined above, we implement a fully functional end-to-end slicing, combining LTE with an SDN and NFV driven CN. Moreover, an empirical evaluation is presented. Thus, firm service guarantees for mission critical infrastructure communication are enabled.

III. 5G End-to-End Network Slicing: Architecture and Concept

Figure 2 depicts our approach to 5G network slicing. Use cases such as SG communication, V2X / Intelligent Transportation Systems (ITSs) or multimedia services are each assigned a network slice tailored to their specific requirements. Devices and users access the infrastructure via the LTE air interface. QoS is enforced through scheduling Resource Blocks via the RAN's eNodeB. In this setup, the Evolved Packet Core (EPC) serves as a simple gateway between the RAN and CN. CN slicing is realized through NFV and SDN, by applying the RAN's QoS parameters to the CN via queues. An SDN-MANO-controller [26] employs the OpenFlow protocol [27] to create and orchestrate configured slices. However, each individual slice is managed by a dedicated SDN controller, granting tenants full control over their virtual infrastructure. In the following, design and implementation of our end-to-end RAN and 5G CN slicing system are described in detail.

A. Long Term Evolution RAN Slicing

As our approach does not utilize separate resources (i.e., spectrum) for instantiating virtual networks, a resource sharing model [5] is required. Therefore, demands in terms of data rate, latency, packet loss and priority relative to other slices are summarized by a QoS Class Identifier (QCI) and respected by the implemented Media Access Control (MAC) scheduler. It creates slices through Dedicated Radio Bearers (DRBs) with Guaranteed Bit Rates (GBRs) and reduces latency for particularly critical slices. Also, a Best Effort (BE) slice without GBR is established for traffic flows that do not fit into the defined use case categories. In the downlink, slice requirements are fulfilled by changing scheduling order based on its priority value. If the total of all data rates requested exceed available capacities, packets are dropped starting from the lowest priority service, i.e., of the BE slice. To prevent starvation of UEs in the BE slice, data rate of critical services may be limited to the GBR, while their other requirements are met. In the uplink, instead of dropping packets, less data is scheduled for non-critical slices. As the scheduler cannot know packet delay ahead of scheduling, delay estimation is performed. Here, we calculate delays based on the time a bearer was scheduled last, which works well for non-bursty traffic with constant data rates.

B. NFV and SDN based Slicing of Wireline Communications

Wireline, i.e., CN slicing is implemented via NFV and SDN, which are key enabling technologies of 5G. Traditionally, the feature set of elements in the communication network is fixed and inseparably linked to hardware. Thus, new functionalities can only be acquired by purchasing new hardware, often associated with high costs, vendor-lock-in, and long deployment cycles. However, NFV addressed these issues by decoupling hardware from software. Network services are provided purely in software as so-called VNFs, which can be run on COTS hardware. Therefore, infrastructure operators are able to flexibly provision and deprovision VNFs, rapidly adapting the network to changing service requirements. To handle the increased dynamic in traffic flows as enabled by NFV, SDN is commonly used for network control. In contrast to traditional architectures, the data and control planes of SDN-enabled networks are separated. The latter is compacted in so-called SDN controllers, which thus provide programmability and centralized management of the control plane. This feature can be harnessed by external entities, such as applications, via the Northbound API. In contrast, the Southbound API serves to reconfigure the data plane, i.e., the physical forwarding of data packets, according to application requirements. The protocol OpenFlow has emerged as the de facto standard for this purpose. Due to its programmability, the SDN controller complements NFV-based infrastructures, by dynamically adjusting the network to VNF demands.

Figure 3 shows the modular architecture of the developed CN slicing system as first introduced in [26]. The SDN-MANO-controller as its core element manages and orchestrates configured network slices and acts as an SDN controller to forward packets between them. It consists of three main parts, the MANO- and SDN controller modules, as well as the virtual network manager. Moreover, Docker [28] is used to instantiate a dedicated SDN controller for each network slice. The SDN data plane is realized with the virtual multilayer-switch software Open vSwitch (OVS) [29], which supports OpenFlow as its Southbound API. Network slices and their QoS requirements are configured through the MANO-module, which adjusts the SDN controller core accordingly. This module then uses OpenFlow to manage the virtual OVS main bridge, which is created on all switches and contains their physical ports. Additionally, for each slice a Hierarchical Token Bucket (HTB) queue is provisioned to provide QoS. One slice can contain multiple queues, enabling differentiation of applications within the overlay network. The virtual network manager runs on each physical switch, handling its main bridge and the slice bridges' QoS queues. Every physical port has an associated virtual port and link. Hence, slice topologies and routes can be created between them flexibly. Dedicated SDN (i.e., slice) controllers, instantiated by the MANO-module via Docker, also employ OpenFlow for managing their respective slice bridges, i.e., their slice.

IV. Testing Environment and Evaluation Scenario

The testing setup and evaluation scenarios of the proposed end-to-end network slicing approach are detailed below.

A. Testing Environment

The wireline CN setup is comprised of four servers with the following resources: Intel Xeon D-1518 processor (four cores at 2,2GHz), 16GB of RAM, and six 1GBase-T Ethernet ports from two Network Interface Cards (NICs) (four: Intel I350, two: Intel I210). Ubuntu Server 16.04.3 LTS (v4.13.0-32-generic x86-64 Kernel) is deployed as Operating System (OS). The sliced SDN switches, as depicted in Figure 2, utilize two of the four servers. Another device is shared by the SDN-MANO and the per slice SDN controllers. They are modifications of the Ryu SDN framework (v4.19) [30] and deployed as container-based VNFs. The remaining server is shared by three iperf2 (v.2.0.10 [31]) instances to recreate use case traffic patterns. As TCP windowing effect could impede a clear view the implemented end-to-end slicing solution's performance, UDP traffic is used. Interference with the data plane is avoided through out-of-band SDN control. Test setup

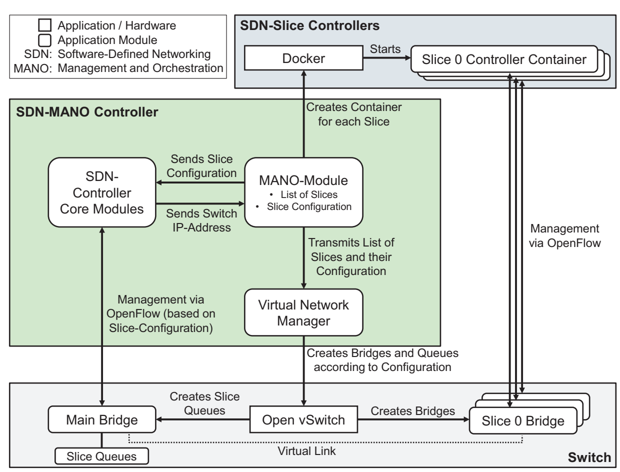

Figure 3: Modular Wireline Network Slicing Architecture [26]

Table I: Used LTE and QCI Parameters [34]

Parameter	Value	
Duplex Mode	Frequency-Division Duplexing (FDD)	
Cell Bandwidth	20 MHz (100 Resource Blocks)	
Radio Link Control (RLC) Mode	Unacknowledged Mode (UM)	
	QCI 3	**QCI 9**
Priority	3	9
Packet Delay Budget (PDB)	50 ms	300 ms
Packet Error Loss Rate (PELR)	10^{-3}	10^{-6}

automation is achieved via a separate management network, handled by a Zyxel GS1900-24E switch.

The LTE subsystem of our end-to-end network slicing solution is implemented using a CommAgility SmallCellSTACK Evolved Node B (eNodeB), running on a CommAgility AMC-K2L-RF2 SDR platform. UEs are custom-built on basis of embedded PCs running Debian Linux, which are equipped with Huawei ME909s-120 LTE modems. This setup offers great flexibility in configuration of the different protocol layers and allows reusing well-established measurement tool-chains used in wired networks. eNodeB and UEs are connected in a wired setup using Radio Frequency (RF) components, including a circulator, attenuators as well as power splitters and dividers. The open source software NextEPC [32] serves as EPC. For the purposes of this work and in terms of user plane traffic, it can be regarded as bit pipe. The EPC's SGi interface, is connected to the wireline SDN test setup and thus to the CN. Table I provides details on RAN parameters used for evaluation of the proposed end-to-end slicing concept.

Precision Time Procotol (PTP) [33] clock synchronization of this setup enables precise measurements. Mean and max. clock deviations of 8 µs and 199 µs are observed, respectively.

B. Evaluation Scenario

In the following, we evaluate the effectiveness of our end-to-end slicing solution considering data rate and delay requirements of SG and ITS communications. For this, the developed scenario follows the layout depicted by Figure 2 and uses the testing setup described in Section IV-A. Three network slices are created via the MANO-SDN-controller with the parameters given in Table II. Both SGs and ITSs slices represent Critical Infrastructure (CI) communication. Therefore, they are categorized as high priority and require low latency as well as robustness. In contrast, the BE slice, which is responsible for handling low priority traffic (e.g. non-real-time multimedia), has a low priority. These levels are mapped to QoS configurations for the RAN and CN by the MANO-controller. In the RAN, high priority slices are realized by UM DRBs, with a GBR of the minimal data rates given by Table II. QCI 3 is selected for the CI slices. BE traffic is handled via the default LTE bearer without GBR and a QCI of 9. Additionally, QoS is continued in the CN, enforcing the same slice constraints behind the EPC. Hence, queues with the priorities and minimal data rates equal to

Table II: Slice Configuration Overview

Slice	Priority	Minimal Data Rate [Mbps]	Max. Delay [ms]
Smart Grids	High	15	10, 20, 100 [35]
Intelligent Transportation Systems	High	20	100 [36]
Best Effort	Low	None	None

those in the RAN are employed. No maximal data rates are assigned. Available excess data rate is dynamically assigned in order of descending slice priority, by the LTE scheduler and HTB algorithm. Hence, only data rates as specified by SLAs are guaranteed. Accordingly, BE data rate is limited, either by queues (downlink) or LTE scheduling (uplink), whenever capacity demands of CI slices require this. UDP-based data traffic in the SG slice is modeled after the IEC 61850 protocol [35]. Depending on the type of action, maximum delays acceptable are 10 ms (line protection), 20 ms or 100 ms (fast/slow automatic interactions) [35]. FCD encapsulated in UDP packets are transmitted in the ITS slice, requiring a delay of $<$100 ms [36]. Devices in the BE slice send bulk UDP traffic. In all cases the payload size is 900 Byte.

As depicted in Figure 4, first BE traffic with a data rate equal to full LTE cell capacity is introduced. Starting from 10 s and 20 s, SG and ITS services transmit 15 Mbps and 20 Mbps, respectively. As aggregate demand exceeds network capacity, the data rate of the lowest priority slice (i.e., BE) is curtailed accordingly. This measurement is repeated 100 times to achieve sufficient statistical significance. Evaluation results are presented and analyzed in the following sections.

V. Evaluation Results

In the following, empirical measurements of the proposed end-to-end network slicing solution are presented. The discussed results are based on the scenarios and physical testing environment outlined in the previous sections.

A. Slice Data Rates in Down- and Uplink

Figure 5 shows the measured layer 4 data rate for a single experiment in the downlink. The dashed line represents the traffic load of 62 Mbps (max. downlink data rate) generated by the BE slice service located in the CN. This data rate can be transmitted over the network until the SG service begins its transmission at 10 s measurement time with a data rate of 15 Mbps. There, an instant reaction of the network slicing system can be observed, which provides the SG service with

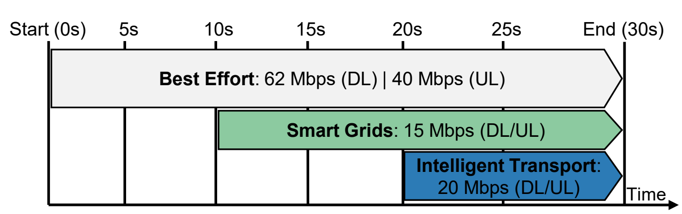

Figure 4: Evaluation Scenario Traffic Flow Sequence

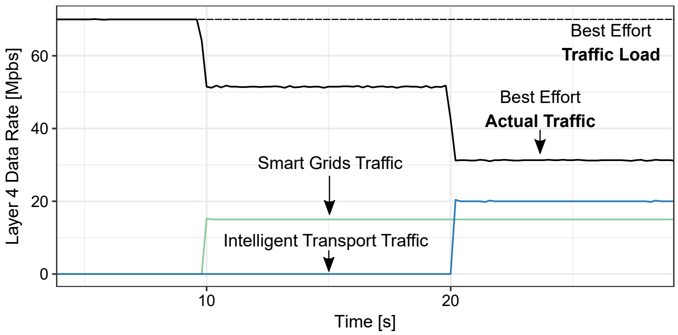

Figure 5: Measured End-to-End Slicing Downlink Data Rates

Figure 7: Measured End-to-End Slicing Uplink Data Rates

the requested 15 Mbps via a reduction of the BE traffic by that amount. This same procedure is repeated at 20 s measurement time, when the ITS traffic load of 20 Mbps is induced. Because both CI slices have the same high priority, the 20 Mbps is also provided by reducing the data rate of the low priority BE slice.

The same measurement is repeated in the uplink, with results presented by Figure 7. Here, the BE slice has a traffic load of 40 Mbps (max. uplink data rate). Similar to downlink measurements, a quick adaption of the network slicing system provides the high priority traffic flows with the requested data rate. Minor fluctuations in data rate occur due to undefeatable caching within the LTE modems and is not a characteristic of the scheduler. Both up- and downlink transmissions show the desired behavior regarding data rate resource allocation.

B. Delay Performance in Down- and Uplink

In Figure 6, downlink end-to-end delays, calculated over all packets, are shown. Moreover, a zoomed section is provided to highlight measurements of both SG and ITS slices. It can be seen that both high priority services have significantly lower delays compared to BE traffic, in the median by a factor of ~ 9. SG and ITS slices achieve median delays of 5.81 ms and 6.05 ms as well as maximum delays of 6.31 ms and 7.83 ms, respectively. Thus, SG and ITS requirements identified in Section IV-B are met. In contrast, BE packets experience higher delays (median: 53.75 ms, max: 62.35 ms) due to the discrepancy between traffic load and assigned capacity, as induced by reserving resources for higher priority slices.

Similar results are observed in the uplink, as depicted by Figure 8. While overall median / maximum delays are higher (SG: 14.59 ms / 26.59 ms, ITS: 18.05 ms / 31 ms), the performance of CI slices still surpasses that of the BE slice (factor $\sim$3.5 in the median). Higher uplink delays are caused by the UEs' need for prior Scheduling Requests (SRs), demanding uplink resources from the eNodeB. The goal of 100 ms max. delay for ITS are also achieved in uplink transmissions. However, the SG slice's performance is only sufficient for slow automatic interactions. The influence of the BE data rate reduction can be observed in more detail, represented by the two clusters of delay values in the violin plot. While the cluster at $\sim$18 ms represents delays before 10 s, the delays forming the median at 58.24 ms occur after the addition of high priority slices. In summary, our approach to end-to-end network slicing achieves significantly lower delays for critical services by transmitting their packets ahead of those from lower priority slices.

VI. Conclusion and Outlook

In this work, we present a prototypical realization of end-to-end network slicing comprising both radio access and core networks. For this, a combination of SDN and NFV in the CN as well as an LTE-based approach in the RAN are used. Designed to take novel principles of 5G into account, a centralized MANO-module is implemented to easily manage network slices spanning multiple technologies in the CN, including different QoS concepts. By providing open interfaces, slice tenants are able to fully manage and control their re-

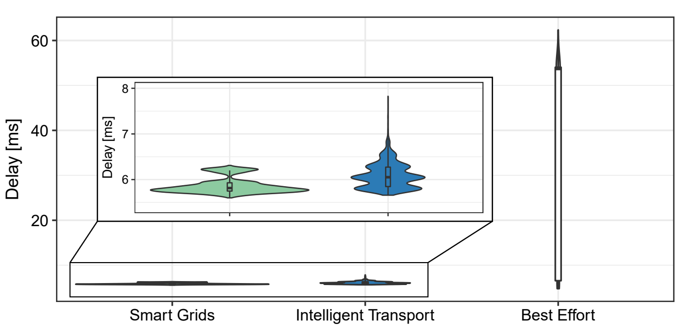

Figure 6: Measured End-to-End Slicing Downlink Delays

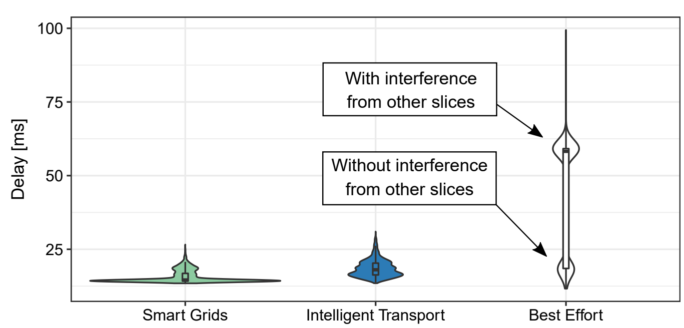

Figure 8: Measured End-to-End Slicing Uplink Delays

spective network slices with own SDN controllers. Moreover, the developed approach is evaluated using a physical testing setup including an SDR platform as well as an SDN/NFV-based hardware testbed. For this, data traffic modeled after CI communication is analyzed based on application-specific requirements in down- and uplink transmissions. The conducted measurements show that data rate resources utilized by low priority slices are instantly handed over to higher priority slices whenever required, both in the RAN and CN. Additionally, delay requirements of ITSs are met both in up- and downlink. In SG transmissions, delay constraints defined by IEC 61850 are met in downlink transmissions, while uplink transmissions are limited to slow automatic interactions. In conclusion, we show that existing technologies like LTE support RAN slicing in a sufficient manner, which highly simplifies the transition to 5G New Radio. However, some high performance applications like SG communication require low-latency enhancements in the uplink. Here, *5G Fast UL* [37] is a promising technique, which is considered in the 5G standardization process to reduce uplink latencies for uRLLC applications. Future work will include interfaces, which allow the MANO-module to create and remove network slices in the RAN. Furthermore, extensions of the RAN scheduler will incorporate multiple UEs and application-specific QoS constraints per slice.

Acknowledgment

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