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Design of a 5G Network Slicing Architecture for Mixed-Critical Services in Cellular Energy Systems

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***Abstract*—The shift towards renewable energies is increasing communication demands, particularly in novel energy grid architectures. One such approach is the concept of cellular energy systems, which divide the grid into regions with the potential to operate independently. Management of the resulting energy flows between and within cells is highly complex. Thus communication becomes increasingly challenging. A promising method for handling the resulting mixed-critical data flows is the fifth generation of mobile radio networks, i.e., 5G. It enables reliable communication in public and private infrastructures via network slicing. Here, a single physical network is split up into multiple slices, each addressing the requirements of various services and devices optimally. This enables cost-efficient communications based on widely available Information and Communications Technology (ICT) infrastructures. In this work we provide an integrated architecture as well as a physical cellular energy system testing setup. This is supported by an open-source 4G/5G software stack and gateways for handling mixed-critical grid communications. The physical testbed is located at the Smart Grid Technology Lab (SGTL) at TU Dortmund university and enables real-world analysis of relevant scenarios. Results illustrate the capabilities of Radio Access Network (RAN) network slicing and provide insights on deploying dedicated mobile radio networks in cellular energy systems with mixed-critical services.**

I. Introduction

Modern energy generation transitions towards renewable, and thus decentralized energy sources, controllable loads and storage (e.g., electromobility). The resulting increase in control activity makes the energy grid increasingly complex to manage. Simultaneously, the deployment of additional power lines should be minimized while existing infrastructure should be used efficiently. To meet this challenge, dividing the power grid into individual cells with decentralized, largely autonomous load and feed-in management has emerged. This concept of cellular energy systems benefits from the use of machine learning methods to optimize regional withdrawal and generation behavior, furthermore enabling the autonomous billing in such energy cells between units by so-called smart contracts [1]. Further services enabled by the use of 5G networks include automated remote maintenance of distributed infrastructures. Such data rate-intensive services can only be deployed within a limited scope with current public Information and Communications Technology (ICT) infrastructures (Long Term Evolution (LTE), etc.), since these lack the necessary functionality for providing Quality of Service (QoS) guarantees in mixed-critical applications.

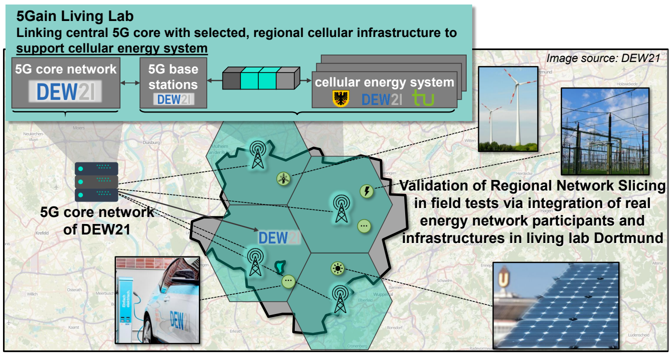

Fig. 1. Concept overview of 5G network slicing providing reliable communications for mixed-critical services in regionally independent cellular energy systems, on the example of Dortmund, Germany. Reliable network slicing, as outlined in this work, is developed and initially tested in the Smart Grid Technology Lab at TU Dortmund university, and will be validated in a *living lab* environment within the 'Kreuzviertel' area.

Within 5th generation of mobile communication networks (5G) network slicing enables the dynamic, dedicated allocation of location-based transmission resources within shared communication infrastructures. In this work, slicing is realized via open-source Software-Defined Networking (SDN) and Software-Defined Radio (SDR) components and evaluated within a realistic cellular energy grid architecture setup. We thus aim to provide reliable communications for smart grid infrastructures within the 5G ecosystem for cellular energy systems. Fig. 1 shows the city of Dortmund including our *living lab* concept, as developed within the 5GAIN research project [2]. It serves to compare the proposed approach of enabling reliable communication via network slicing, as outlined in this paper, within a real deployment area. This constitutes the basis for the overall architecture developed and outlined in this work.

The remainder of this work is structured as follows with related works highlighted in Sec. II, providing insights into the state of the art concerning network slicing for cellular energy systems. Next, Sec. III is divided in subsections to provide an overview over the architecture used for the cellular energy system and the communications perspective to provide network slicing functionality. The proposed architecture is evaluated in Sec. IV, which also includes an overview of the energy systems of the on-campus Smart Grid Technology Lab (SGTL) setup and initial over-the-air measurements within this realistic environment. Finally, a conclusion is given in Sec. V and complemented by an outlook on future works.

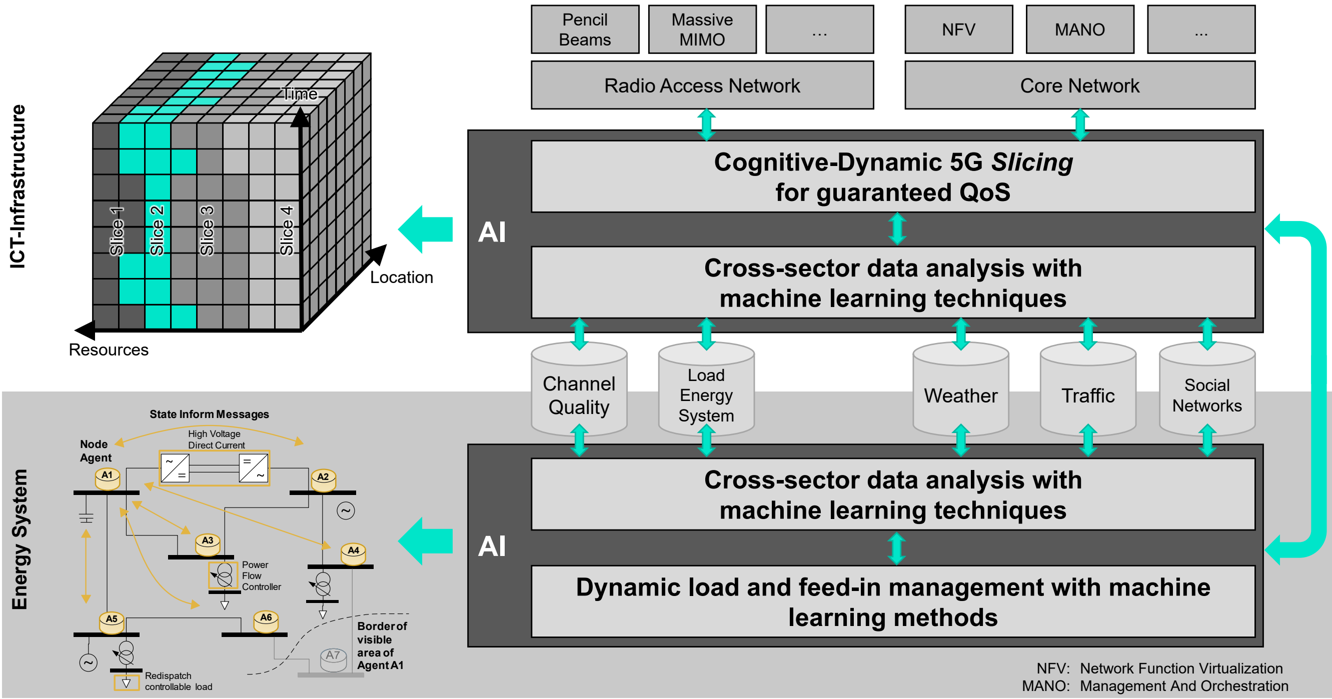

Fig. 2. The ICT infrastructure supplements the cellular energy system by utilizing machine learning techniques to allocate resources according to the priority of each network slice. Data analysis is conducted for, e.g., current channel quality, traffic peaks as well as long-term developments in weather. From the energy system perspective, a similar prediction is used to anticipate, e.g., peak loads. An agent-based system is deployed to gather, analyze and transmit the collected data towards a centralized energy data hub for further processing.

II. Related Work

Typically, latency requirements for smart grid communications are considered among the most challenging applications, with end-to-end demands of below 5 ms. Therefore, several existing works focus on ICT delays in general and smart grid scenarios in particular. In [3] the integration of cellular networks under aspects of renewable energy usage and architecture is analyzed and a proposal for smart grid architectures is derived from a grid operator's perspective. The authors of [4] conducted a literature survey regarding cellular communications for smart grid applications specifically tailored for neighborhood area networks. Here, the idea of regional cellular networks for Distributed Energy Resources (DERs) is picked up, while highlighting challenges remaining with the LTE standard. The authors of [5] define a Web-of-Cells control architecture, emphasizing the benefits of cellular energy systems and the resulting demand in communications. Due to the various challenging requirements, current 5G networks aim to provide specialized technologies to address heterogeneous use cases targeting a high performance level for throughput, latency and scalability. With the concept of network slicing, reliable mission-critical communications are made possible, by flexibly assigning dedicated radio resources to individual User Equipments (UEs). The concept of network slicing is based on the foundations of SDN and Network Function Virtualization (NFV), which together enable programmability, virtualization and isolation of network resources. In this context, the previous work by [6] serves as starting point for this work, showcasing a Round Robin (RR) based air interface scheduler for reserving resources according to service priority in the Radio Access Network (RAN). Over the past years research into network slicing shifted from the core network towards the much more volatile RAN, which needs to consider further parameters such as changing channel conditions. The authors of [7] give an early survey of the state of the art in 5G network slicing, still providing insightful resources. A common framework is formulated inheriting the classification of different approaches to network slicing as well as the different architectural layers. The ability to implement Management and Orchestration (MANO) entities to control and manage network slices allows also for end-to-end network slicing within the 5G networks. However, in contrast to the core network, the resources in the RAN are much more volatile and virtualization here is still under research and hence part of this work. The authors of [8] provide an insightful literature review for 5G for smart grids in general and the technology of network slicing in particular. In the work of [9] applications for 5G network slicing are formulated and defined for the different architectural levels of a smart grid. Following the simulation-based approach in [10], where slicing is enhanced by using the so-called configured grants mechanism, proactive slicing aims to provide resources before an UE is actively asking for them. Thus scheduling requests and their latencies are eliminated. Yet, those works do not specifically focus on integrating these approaches in a comprehensive architecture and a real-world cellular energy system, as targeted by this work.

III. Predictive Regional Network Slicing for Cellular Energy Systems

The following subsections provide an overview of the architecture on which the regional network slicing for cellular energy systems approach is based on. The architecture is split into two main categories, starting with the cellular energy system itself. This is followed by the network slicing based communication methodology for enabling mixed-critical services and support stable grid operation.

A. Cellular Energy Systems

As mentioned in the introduction, the modern energy grid shifts towards decentralized energy distribution and thus requires enhanced communication between the devices to control and monitor them. Therefore, the approach of dividing the grid into distributed energy cells can be used. However, this scenario presupposes a high degree of networking among the players involved, which in turn increases the overall complexity of the energy system. To provide such networking, the 5G communications standard with the capability of slicing physical networks is evaluated under real-world circumstances. The complexity of the energy system is reduced, by relying on 5G communication between energy nodes, using regional network slicing. This allows slices to be adapted to the respective regional differences, e.g., in terms of data volume, and to be split across several mobile cells. Using machine learning algorithms, the provisioning of resources within each network slice can be automated and thus monitoring and control of largely autonomous cellular energy systems is enabled.

The imbalance between energy generation and withdrawal, caused by volatile feed-ins, increasingly endangers the stability of the energy grid. Therefore, the need for new concepts of network management arises to enable comprehensive, continuous monitoring and control of energy systems down to the energy distribution network. The network management is especially crucial for handling the significant demands on the quality of service for the superimposed ICT infrastructures regarding transmission latency, availability and scalability. In the same course, high cost efficiency in the construction and operation of communication networks is pursued. This is where cellular energy networks come into play, where the energy grid is divided into sections, i.e., cells, which act semi-autonomously and establish a decentralized load and feed-in management. These cells comprise generation units, loads and storage facilities including coordination of power generation and consumption. In future research this management can be improved by utilizing methods of Artificial Intelligence (AI). The focus of this work lies on providing connectivity for the acquisition and processing of data gathered from the energy grid within the cell. Here, agent systems are used to enable real-time capable control algorithms in combination with edge-cloud approaches. The communication for these agents is established by using LTE gateways enhanced with the capability of slicing the RAN for each priority level.

B. 5G Network Slicing as Key Enabler

The technology of network slicing builds on the concepts of SDN and NFV. With the concept of NFV, functions such as gateways or firewalls can be virtualized and with this, regular Commercial of-the-Shelf (COTS) hardware can be used to deploy new functions via a virtualization layer instead of having to buy new specialized hardware for each new function. This leads to the need of further orchestration, since the virtualized functions can claim resources from different physical hardware, which again leads to higher flexibility and more cost and energy efficiency. To provide complex networks with several virtualized functions with an entity to control all of them centrally, the concept of SDN is introduced. Here, the so-called data plane is decoupled from the control plane, which leads to the capability of controlling a complex network with a single entity, the SDN controller. This hardware is typically located at data center environments and communicates to devices on the data plane. Therefore, these devices can be realized as more simple switches to just forward packets based on rules set by the controller. With 5G, the 3rd Generation Partnership Project (3GPP) reworked the core network (5GC) and builds on top of the previous mentioned technologies. Thus, the core network supports a Network Slice Selection Function (NSSF), enabling for end-to-end network slicing by selecting a set of sliced instances of the network to serve the UE. This enables logically isolated virtual networks on top of a physical network. Therefore, also public networks can be used to provide mission-critical communication to energy systems, while keeping costs low. Additionally, this leads to increased flexibility in providing new services within the infrastructure and allows for rapid deployment of devices. For the NG-RAN, the user and control plane are also decoupled and devices are split into central and distributed units (CU/DU). In Fig. 3 our approach to realize network slicing towards 5G is depicted.

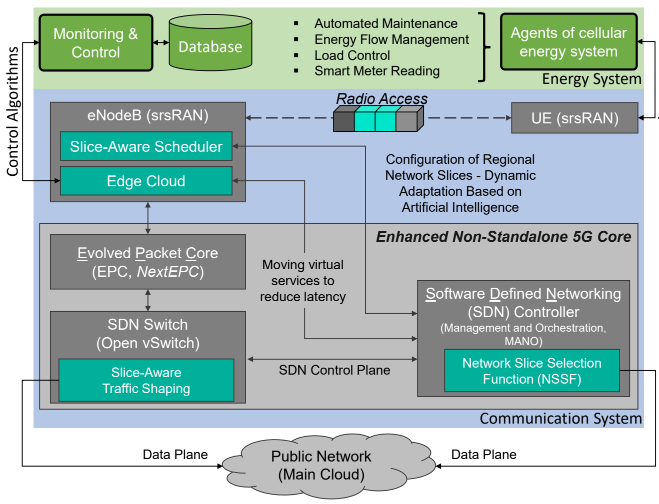

Fig. 3. Framework for providing network slicing in the air interface. It is based on Commercial of-the-Shelf (COTS) hardware and an open-source radio software stack, enhanced with 5G features to enable network slicing in the RAN. This enables rapid deployment and long-lasting support of devices while reducing the risk of vendor lock-in.

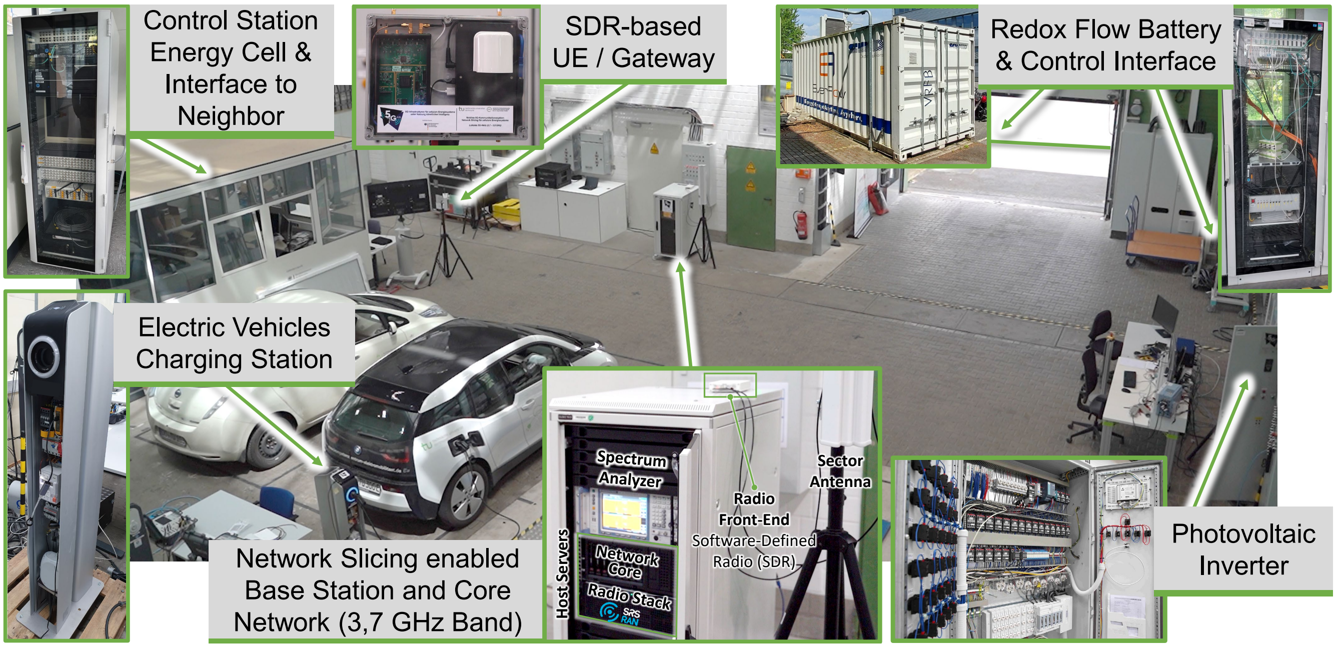

Fig. 4. The proposed scheduling approach, for enabling reliable communication using the technology of network slicing, is tested within the Smart Grid Technology Lab at TU Dortmund university. The agent system is deployed for representative energy loads and generators comprising two electric vehicle charging stations, an inverter PV system and a redox flow BESS. Furthermore, two cells can be deployed to showcase regional network slicing capabilities.

We are using the concepts outlined above to provide gateway functionalities to the different agents for transmitting control and monitoring data over the air interface. For this, the works of [11] are advanced utilizing containerized applications to provide base station and UE capabilities to COTS hardware. Therefore, hardware and software are decoupled and allow deployment in production sites more easily. The usage of Small Form Factor (SFF) PCs in combination with SDRs enables for integration within existing infrastructure, instead of re-designing energy systems to support mobile radio gateways. The functionality for sending and receiving packets via the air interface is provided by the srsRAN project [12], which implements an open-source full LTE software stack with 5G Non-Standalone (NSA) enhancements as well as a custom scheduling for network slicing. For the core network, the software of nextEPC [13] is used, also in containerized form and running on the same hardware as the base station. This is possible by deploying virtual switches to enable the communication of the isolated containers of the core network and the base station. Furthermore, this allows for fine-granular tuning of packet streams being sent via the air interface and control data via a backup WiFi network, which is depicted here as public network or the main cloud infrastructure. Controlling packet streams can be realized with a dedicated SDN controller, e.g., within another container or on a different device in the network. According to Fig. 2, the framework can be enhanced by utilizing Machine Learning (ML)-based methods to provide automation and dynamic resource allocation depending on current channel conditions or traffic loads within the network. This can be combined with the monitoring and analysis of the devices in the energy systems. Data analysis is aimed to be collected and transmitted towards an Energy Data Hub (EDH), which provides the schedulers with trained models to predict data traffic and adjust slicing capacities accordingly. Thus, the required radio resources can be reserved exclusively, precisely and adapted to the dynamic requirements of energy industry applications by expert configuration and, in future work, by self-regulating algorithms. By dynamically allocating these resources, high costs in form of reserved, but unused resources are mitigated. A priority-based approach ensures the security of supply, since resources are isolated for each connected agent. That is to say, the critical network operation applications are prioritized over less critical maintenance or supervision applications. The key cost reduction is achieved by the ability to use public networks and still guarantee resources via network slicing, instead of utilizing private, dedicated networks to achieve the same availability. This work provides the baseline for the comparison of such a sliced network within a private 5G campus network over a realization within a public infrastructure in future works.

IV. Evaluation of 5G Gateways for Agent-Based Communication

This section comprises a description of assets used within the Smart Grid Technology Lab (SGTL)[1] and the underlying setup description for enabling radio communication. Moreover, initial results in deploying gateways to provide network slicing based connectivity for energy devices, as conducted within the realistic environment of the SGTL, are discussed.

[1]http://smartgrid-tec-lab.com/

A. Smart Grid Technology Lab Setup

Building on previous works, we provide wireless communication on the campus network frequencies (3.7 GHz to 3.8 GHz) for several devices. The campus network frequencies are defined by the Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway (Bundesnetzagentur) especially for the purpose to build and operate private networks based on the 5G standard. The SGTL comprises a variety of energy devices to be included into the scenario and communication network. For the EV Charging testbed, there are in total four vehicles available, which can be charged at either a Phoenix Contact or Wirelane CC612 EV Charge Control. The test vehicles to provide realistic charging behavior include a Nissan Leaf as well as a BMW i3. Next, there is the testbed for photovoltaic systems emulation which includes a Power Hardware-in-the-Loop (PHIL) setup. This setup enables for interfacing physical PV-inverters with simulated PV-systems. The whole testbed is connected with the test network of the laboratory enabling the realistic reproduction of energy generation. For storing energy, the SGTL is equipped with a Vanadium redox flow BESS inheriting six stacks in two groups. These enable for a maximum power output of 30 kVA and a total capacity of 120 kWh. They are connected to grid inverters and include a battery management system, allowing for monitor and control operations. Data can be read out using the Modbus/TCP protocol within the facility and thus act as another agent in our cellular energy system architecture. For the emulation of larger energy cells, there are power hardware in the loop systems extending the testing capabilities. A Real-Time Digital Simulator (RTDS) enables the emulation of urban areas, interfacing with two groups of four modules power amplifiers with a rated power of up to 100 kVA per group. An SDR-driven base station is utilized, attaching three UEs/gateways for grid devices within the SGTL. These comprise an Electric Vehicle (EV) charging station, a PV inverter and a redox flow BESS. The corresponding agents are hosted on an embedded platform (Raspberry Pi), which serves as device for reading and processing the raw data of the energy devices. For the connection via a campus network, we deployed Intel NUCs with a Core i7-6770HQ, 16GB RAM and Ubuntu 20.04.2 LTS (kernel: 5.11.0-34-lowlatency), which are connected to an Ettus Research USRP B210. The base station consists of a server powered by an AMD Ryzen 5900X CPU and 32 GB of RAM. The enhanced LTE stack is based on a pre-release of srsRAN 21.04. The NUCs serve as gateways for the embedded systems. Thus, they are synchronized using the Network Time Protocol (NTP). For validation of network slicing capability, constant traffic is induced using iPerf v2.0.9.

B. Initial Evaluation Results

In Tab. I the radio configurations for the scheduling of network slices are given. For the measurements, packets are sent every 1 ms. The bandwidth is set to 5 MHz in Frequency Division Duplex (FDD) Mode. Therefore each direction (Up-/Downlink) uses specific spectrum. The Modulation and Coding Scheme (MCS) is set to seven, i.e., Quadrature Phase-Shift Keying (QPSK) modulation according to table 8.6.1-1 [14], while Subcarrier Spacing (SCS) is based on the standard LTE frame length, correlating to 15 kHz in 5G numerology.

TABLE I
RADIO CONFIGURATION FOR SLICE SCHEDULING

Transmission Time Interval (TTI) [ms]	Channel Bandwidth [MHz]	Subcarrier Spacing (SCS) [kHz]	Modulation and Coding Scheme (MCS)	Maximum Throughput [Mbps]
1	5	15	7 (QPSK)	2.18

The test setup comprises three UEs connected to a base station running our proposed network slicing scheduler. Each of the slices is prioritized differently by the scheduler, according to their respective Cell Radio Network Temporary Identifier (C-RNTI). The scheduler provides each UE resources based on a token bucket principle. The lowest priority slice receives one token, the next priority two tokens and the highest priority receives three tokens. However, if resources remain unused, higher priority slices are allowed to use those resources of the higher prioritized slices. The devices are located within the SGTL and communicate via the previously introduced setup over the air interface with locations as depicted in Fig. 4. The location includes the EV charging terminal, PV inverter and redox flow battery control interface.

In Fig. 5 results obtained for the throughput measurements are presented. For the measurement User Datagram Protocol (UDP) packets are customized to contain 735 Byte of payload. Due to the robust MCS of seven, uplink direction and protocol overhead, the maximum achievable throughput with our setup is at 2.18 Mbps. The best effort slice transmits with a mean of 2.09 Mbps, so the bandwidth is not overutilized and packet loss does not occur. The low priority slice aims to transmit 800 kbps, whereas the high priority slice

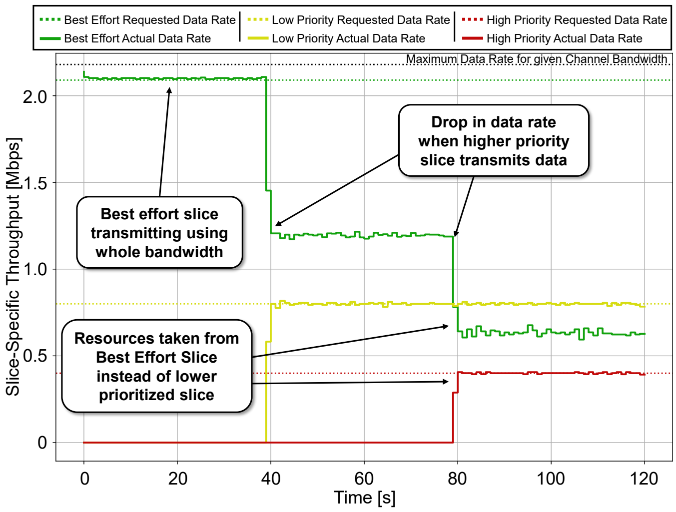

Fig. 5. Data rates in uplink direction for low/high priority and best effort slices, as measured with a LTE-based cell enhanced with network slicing functionality. Resources are assigned to UEs according to slice priority, resulting in hard service guarantees for critical low and high priority services, while best effort drops. The setup is deployed within the SGTL with UE gateways providing communication for energy system agents including an EV charging station, a redox flow battery as well as a PV inverter.

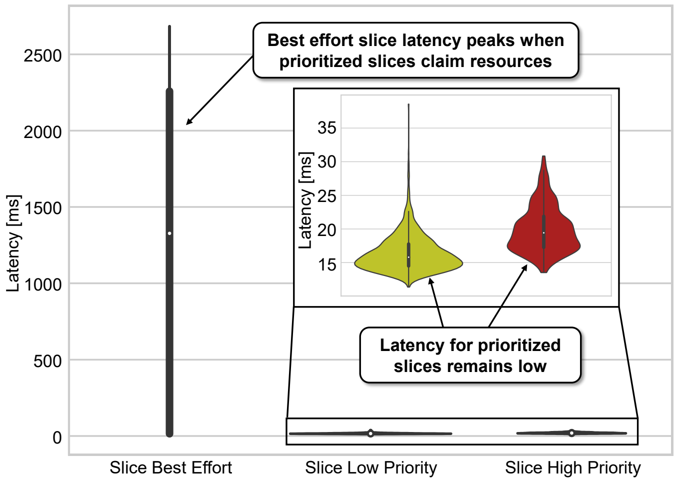

Fig. 6. Observed latency of critical services remains at a low level while best effort latency peaks due to the loss of resources. These peaks increase with every additional prioritized slice claiming resources for transmission. Therefore, packet loss is experienced by the best effort slice only, whereas packets are received regularly for low and high priority slices.

transmits 400 kbps. Therefore the bandwidth is not sufficient for all slices to transmit simultaneously. The UEs represent prioritized slices, i.e., each UE is the only tenant of a specific slice. Achieved throughput is demonstrated over the time of 120 s on the x-axis. Every 40 s, another, higher prioritized slice demands resources, thus a less prioritized slice needs to give up bandwidth. The measurement starts with the best effort slice using the whole bandwidth and therefore using also the unused tokens of higher prioritized slices. However, when the UE of the low priority slice begins transmission, the data rate drops according to the amount of resources needed by the prioritized slice. Finally, when the high priority slice begins its transmission at timestamp 80 s, even more resources are taken from the best effort slice instead of the low priority slice. Thus, all of the prioritized slices receive the specified bandwidth for transmission. The outliers in data rate originate from artifacts in the process of averaging the data rate per second. In Fig. 6 the latencies resulting from the prioritization of resources for each slice are depicted. For this, the devices are software synchronized by using NTP utilizing the chrony implementation. The latency for the slices low and high priority remain on a steady latency level below 40 ms, whereas the best effort slice latency peaks with each loss of resources due to transmission of higher prioritized slices. Within the data streams of priority slices the packet loss is 0 % during the experimental evaluation. However, the best effort slice experiences packet loss proportional to the amount of data rate which exceeds the assigned capacity. This can be mitigated by provisioning additional radio resources. However, due to the financial costs of exclusive radio frequency bands, this step should only be taken if mission-critical requirements can not be met, i.e., if communication demands outstrip available 5G capacity. Improved latency and data rates can be achieved with more optimized or possibly non-SDR radios, additional frequency resources and less robust (i.e., higher) MCS.

V. Conclusion and Outlook

In this work we propose a framework to enable cellular energy systems using 5G network slicing. This enables smart grid operators to connect devices with reduced costs and effort on basis of private or public communication infrastructures. The architecture integrates 5G gateways and agents, providing information over data and energy flows, which can be collected in a centralized entity. This also enables future AI algorithms to learn and provide trained models for prediction and resource allocation. First results demonstrate the hard prioritization of mixed-critical services in a virtualized RAN setup within a purpose build and realistic cellular energy system laboratory environment. Data rates adjust to changed prioritization within less than one second, proving the approach's flexibility. For future work, the architecture's Application Programming Interface (API) for providing access for ML algorithms on the base station and enabling online learning capabilities to dynamically adjust resource provisioning for each slice. Thus, network slices can adapt automatically to worsened channel conditions and novel data traffic. Also, the *Open RAN* concept's RAN Intelligent Controller (RIC) will be used to host microservices supporting smart grid communications.

Acknowledgment

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