

Software-Defined End-to-End Evaluation Platform for Quality of Service in Non-Standalone 5G Systems

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Abstract—The fifth generation of mobile communication (5G) will support a much broader spectrum of quality of service (QoS) profiles than its predecessor long-term evolution (LTE). These improvements are enabled by new features such as software-defined end-to-end network slicing, which concern both the core network and the air interface. However, the current vision for the actual rollout is a smooth transition from LTE: First, the new radio (NR) base stations are integrated into the existing LTE network infrastructure in a configuration called non-standalone mode. At a later stage, the core network will be replaced by a complete and standalone 5G network. The long transition period using the previous generation's core will pose challenges in delivering some of the promised advantages of 5G networks. This work addresses these shortcomings of non-standalone operation. We propose a development and evaluation platform capable of integrating QoS and investigate ways of enabling 5G performance at a much earlier stage of the generation transition. In the experimental setup, an LTE air interface is augmented by a software-defined radio (SDR) based NR link at 28 GHz, while end-to-end network slicing functionalities are implemented via software-defined networking at the core as well as the radio access network. First evaluations prove that the proposed system is capable of reliably ensuring QoS.

I. INTRODUCTION

As one of the main goals for the fifth generation of mobile communication (5G), the implementation of quality of service (QoS) will play a major role in the development of upcoming mobile networks. Shared infrastructure will be required to handle multiple different use cases that demand a variety of contradicting communication guarantees. Three main service classes representing highly diverse QoS requirements are defined [1], [2]: ultra-reliable low latency communication (URLLC) for critical infrastructure communication, massive machine type communication (mMTC) for internet of things (IoT) applications, and enhanced mobile broadband (eMBB) for end user multimedia services.

Since the objective of QoS is often to support application oriented service levels, the aforementioned service classes are application related rather than device specific. A single user device can connect to the network through multiple traffic flows, each configured with different parameters related to the individual application's requirements. For example, this applies to critical infrastructures like unmanned aerial vehicle (UAV) aided search and rescue (SAR) missions, where rescue robotic applications like control links to remotely operated

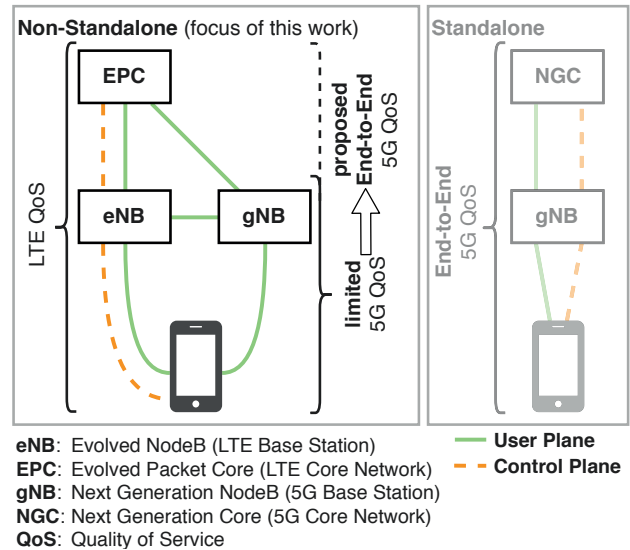


Fig. 1. 5G's non-standalone and standalone operation modes as proposed by 3GPP. In non-standalone mode, the conventional LTE infrastructure is used for control plane, while 5G new radio base stations are expected to supply additional resources for user plane traffic. In contrast, the standalone mode uses 5G's core network which enables holistic 5G QoS guarantees.

UAVs take on a prioritized role within the shared mobile radio network.

Fifth generation networks will operate in one of the two modes shown in Figure 1, namely non-standalone (NSA) and standalone (SA). The NSA mode represents the first step in the transition towards 5G. In this phase, existing long-term evolution (LTE) infrastructure consisting of base stations (eNB) and the evolved packet core (EPC) coexists with 5G new radio (NR) base stations (gNB). As a consequence, the control plane in early fifth generation networks is handled by fourth generation components. In SA mode, the next generation core (NGC) is introduced, leading to a full 5G system. Hence, before reaching the point of standalone operation, QoS implementations will rely heavily on the deployed LTE infrastructure. [3]

In LTE networks, a number of QoS profiles called QoS class identifiers (QCIs) are defined. Table I lists some selected identifiers and their requirements as of Release 15 [4], which is also the introduction point of the 5G NSA mode. Note

TABLE I
SELECTED QoS CLASS IDENTIFIERS AND THEIR PARAMETERS [4]

	QCI 9	QCI 3	QCI 84	QCI 85
Priority	9	3	2.4	2.1
Packet Delay Budget (PDB)	300 ms	50 ms	30 ms	5 ms
Packet Error Loss Rate (PELR)	10^{-6}	10^{-3}	10^{-5}	10^{-5}

that QCIs 84 and 85 were not present in prior releases, which were almost exclusively focusing on LTE and its extensions. QCI 3 represents the most demanding QoS parameter set in LTE, whereas default traffic is handled with QCI 9. It is worth noting that applications with packet delay budgets (PDBs) lower than 50 ms are not addressed in present LTE networks. Using only the QCI framework introduced above, some major functionality of 5G cannot be realized until NGC development is finished and the core has been integrated into public mobile networks. This may be preceded by a lengthy non-standalone transition period.

To address this issue, we introduce an end-to-end system-of-systems, which is capable of delivering 5G QoS in NSA mode. The underlying system parts and concepts have already been analyzed and validated independently in preparatory works: To study the new radio mmWave characteristics, the need for precise antenna alignment especially in highly mobile environments is experimentally evaluated in [5]. With *tinyLTE*, a lean mobile network design suitable to run on commercial off-the-shelf (COTS) hardware using open-source implementations is presented in [6]. Furthermore, the development of our network slicing evaluation platform is presented in [7], [8]. By combining these prior works into an end-to-end system, we evaluate key concepts and their synergies by means of a holistic mobile radio network development platform.

The remainder of this work is organized as follows: In Section II, an extract of most significant related work is exposed by not only presenting the overall 5G system concept but also recent enhancement proposals. Our proposed architecture of an end-to-end platform is discussed in Section III. Details on the implementation and first performance evaluation of our proposed system approach follow in Section IV. A summary concludes this work in Section V.

II. ON 5G'S MAIN CONCEPTS AND RECENT PROPOSALS

With 5G, the requirements defined in the IMT-2020 specification [2] will be addressed: The introduction of eMBB to overcome increasing data rate demands, time critical application support through URLLC, and scalability in terms of high amounts of IoT devices as covered by mMTC. These features are to be implemented by several key enablers briefly outlined in the following.

A. New Radio's Utilization of mmWave Communication

The term new radio (NR) signifies various changes on the air interface itself as well as the radio access design. Compared to 5G's predecessor LTE, the physical resource structure is more flexible due to scalable subcarrier spacing and slot durations.

To support low latency use cases for example, shorter symbol durations and so called mini-slots are introduced. [9]

Particularly, utilizing frequencies in the millimeter wave (mmWave) domain (e.g. at 28 GHz) is an essential novelty to public land mobile networks. Because of the large available spectrum in this frequency domain, reaching the demanded data rates for eMBB use cases may be possible. Although the radio propagation conditions are far more challenging than at conventional sub 6 GHz frequencies, it is believed that high gain antennas can more than compensate the increased free space path loss [10]. However, less diffraction, higher penetration loss and line-of-sight (LOS) requirements may complicate mmWave radio communications. Radio channel measurements and modeling approaches for these new frequency ranges are comprehensively summarized in [11]. On the operational side, the antennas' high gain comes at the price of high directivity, which necessitates a precise alignment of narrow main lobes (*pencil beams*). In case of antenna arrays, this alignment is achieved by beamforming. While broadcasting concepts will need to be reconsidered, pencil beams allow for a considerable spatial reuse of radio resources [12].

In [1], [9], [13], authors present comprehensive overviews of challenges and benefits of supposed essential features of 5G NR.

B. Resource Bundling Through Cloud RAN

Resource efficiency is a central topic in 5G radio access network (RAN) design. While previous generations of mobile networks were built from distributed base stations and centralized core network entities, the cloud RAN (C-RAN) architecture aims to virtualize and move some of the radio access functionality from base stations to centralized compute resources [1]. To that end, base stations are split into central units (CUs) and distributed units (DUs) connected via two networks: The core-to-CU *backhaul* and the CU-to-DU *fronthaul*. While the original idea of C-RAN was to send radio samples over the fronthaul, the associated high bandwidth and timing requirements for the fronthaul have inspired an expansion of the concept towards separating nodes at higher layers of the radio protocol stack [14].

Recent works formulate the choice of split as an optimization problem and propose algorithms to optimize C-RAN configurations based on network requirements [15]. In [16], the high variability in fronthaul requirements posed by different splits leads to the idea of supporting fronthaul and backhaul as well as the core network in a shared *crosshaul* network. This common infrastructure is supported by software-defined networking (SDN) components to guarantee QoS requirements of the different network entities. Additionally, frameworks to optimize crosshaul routing and topology together with a conceptual experimental demonstration of the system are proposed in [17].

C. Paradigm Shift at the Core Network

In 5G, network slicing is introduced as a fundamentally new concept [18]. This technology employs so called *network*

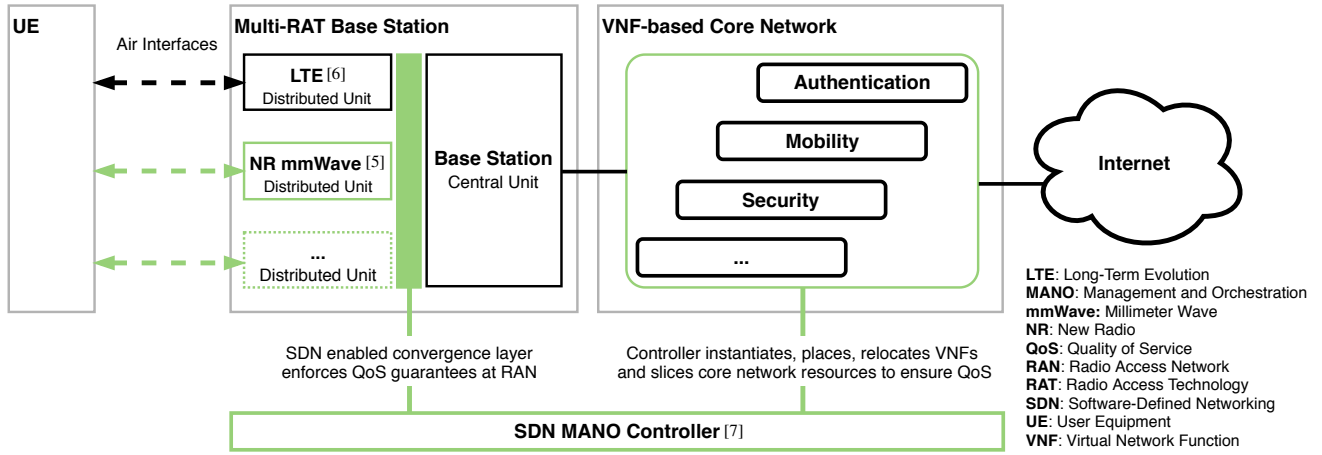


Fig. 2. Proposed software-defined end-to-end network slicing architecture integrated into 5G's non-standalone mobile network approach. The SDN MANO controller ensures quality of service (QoS) on each end-to-end slice by managing virtual network functions (VNFs) inside the core network as well as radio access technologies (RATs) at base stations.

slices, which are logical end-to-end networks realized on top of a common physical infrastructure. These slices, which act exactly like a physical communication infrastructure, can be leased to third parties with diverse use cases and requirements. To ensure QoS constraints of every use case simultaneously, fractions of available computing, storage or networking resources can be assigned to network slices dynamically. In doing so, the network operator has to ensure isolation between different slices, so that faults in one slice do not affect the others.

In mobile core networks (CNs), SDN and network function virtualization (NFV) are the most promising candidates for implementing network slicing [19]. As a first step towards 5G, the following related works address the use of SDN and NFV in LTE CNs: An integration of the LTE EPC into an SDN-based as well as NFV-based architecture is presented in [20]. Here, the results indicate, that an SDN-based EPC is well suited for handling large amounts of user data. Their NFV-based EPC, however, is better at processing large signaling loads. In contrast, our work aims at employing both networking technologies in combination with QoS queues to implement end-to-end network slicing.

The works showcased in [21] and [22] highlight the impact of state synchronization between different virtualized EPCs. While these works show the influence of multiple core networks on each other, our work focuses on examining traffic isolation between the virtualized submodules of an EPC.

Finally, the work presented in [23] emphasizes the significant benefits of using containers in NFV deployments while recommending strict performance isolation. We additionally use QoS queues to ensure traffic isolation and eliminate negative interferences between slices [7].

III. PROPOSED END-TO-END PLATFORM

Following the model of the non-standalone mode, we integrate a gNB into an established LTE network: Our *tinyLTE* system [6] forms the basis of the proposed platform by hosting core network, RAN and user equipment components, already

incorporating NFV concepts. Figure 2 depicts the overall system concept, whose detailed description follows in the remainder of this section.

A. SDR-based Air Interface

Utilizing software-defined radio (SDR) technology, the LTE DU can operate at any frequency up to the device's limit at 6 GHz. The mmWave transceiver system as illustrated in [24] operates in parallel as a NR link at 28 GHz. With a bandwidth of 800 MHz, it is designed for application level data rates in the domain of several Gbit/s. As indicated by the third distributed unit in Figure 2, the proposed system is designed in such a way that additional radio access technologies can be integrated in the future.

Depending on the functional split configuration, the gNB may be part of an additional carrier like in the well-known carrier aggregation (CA) or act as a secondary base station like in dual connectivity (DC). In CA mode, with a split at medium access control (MAC) layer, both carriers can be aggregated in downlink, uplink or both directions to build a CA operation mode. Due to the shared scheduler instance, the component carriers have to be precisely synchronized, imposing significant latency constraints on their interface. Alternatively, the split may be moved to the packet data convergence protocol (PDCP) layer which is analogous to the DC operation mode. Since this split happens at a higher protocol layer, fronthaul requirements are reduced at the price of moving some processing power to the DUs [3], [25].

B. Functional Split and Virtualization

As mentioned above, *tinyLTE* already implements virtual network functions (VNFs) by operating network entities as software containers hosted on COTS hardware. Encapsulating RAN components in this way also allows execution in the cloud (i.e. C-RAN).

To integrate the NR air interface into the *tinyLTE* system, we follow an implementation path close to the concept of

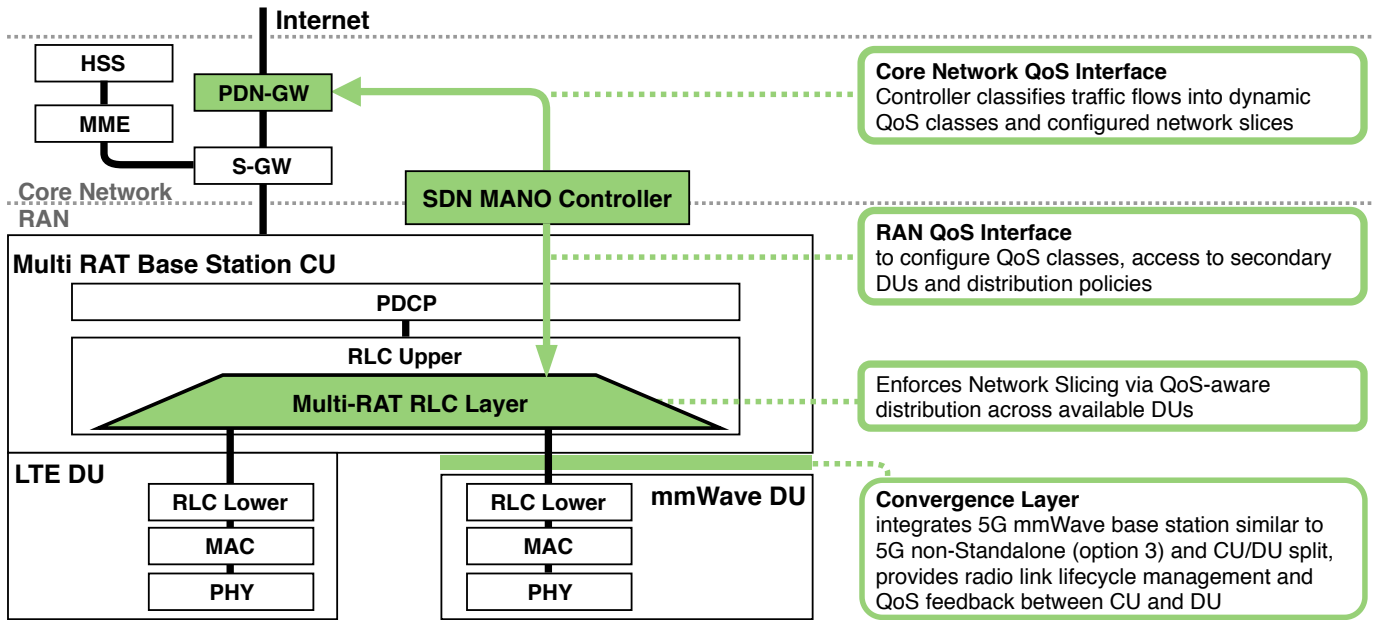


Fig. 3. Implementation characteristics. The functional split is implemented inside the base station between the RLC upper and RLC lower layer. It enables the incorporation of an additional DU, which in our case is a 5G NR mmWave DU affiliated as secondary base station for the purpose of supplying E-UTRA-NR dual connectivity (EN-DC). Our SDN MANO controller not only interferes at core network level but also at this split level to allow for traffic control within the complete operator part of the mobile radio network.

E-UTRA-NR dual connectivity (EN-DC) with split bearers [26]. In EN-DC, a master base station (MeNB) is supported by a secondary NR base station while being connected to an LTE core network. The split bearer approach is transparent to the system at the radio bearer level, i.e. the aggregation of the two air interfaces happens below the PDCP layer. Flow control decisions are performed at the master (LTE) node which may forward data to its own radio link control (RLC) layer or pass it to a secondary node, the NR mmWave node, via a joint X2/F1 interface. This interface combines the interconnection of base stations (X2) and realization of the CU-DU concept (F1) similar introduced in [3], [26].

The functional C-RAN split implemented in this work is motivated by this mode of EN-DC, separating centralized and distributed units at the PDCP level (more precisely below the RLC upper layer). As a consequence, signaling required to coordinate between the two nodes happens only inside the CU part, making the X2/F1 interface a purely virtual network link within the resources of the centralized instance. This approach ensures optimal performance of inter-node signaling while not adding load to the network infrastructure.

C. NFV/SDN-based Core Network Slicing

In order to support multiple applications with highly diverse requirements and importance, we introduce an end-to-end network slicing functionality based on SDN and NFV concepts. The SDN and NFV management and orchestration (MANO)¹ capabilities of our system are implemented by our

SDN MANO controller, previously presented in [7]. It acts as the programmable control plane of the holistic communication network (thus, depicted as underlying instance in Figure 2). The SDN MANO controller also manages VNFs by means of a virtualization layer between hardware and network functions, enabling the use of COTS hardware. Furthermore, VNFs may be deployed and withdrawn flexibly depending on available hardware and desired network configurations.

In summary, our SDN MANO controller facilitates deploying any network service topology based on VNFs and simultaneously acts as an SDN controller. SDN-driven QoS queues ensure QoS and traffic isolation between different network slices. Finally, these functionalities enable various user requirements to be met on the same physical topology simultaneously by dynamically instantiating CN components and orchestrating the aforementioned RAN features.

IV. CONCEPT EVALUATION

In the following, the implementation of the proposed software-defined end-to-end network slicing architecture as well as the overall laboratory setup are specified. On this basis, an exemplary test sequence is repeatedly carried out to allow for an illustration of the realized system concept by means of measurement results and their subsequent statistical evaluation.

A. Implementation Characteristics and Laboratory Setup

The implemented functional split of the base station into the LTE DU part and the CU part is depicted in Figure 3. Similar as proposed by option 3 in [3], the separation is carried out between the RLC upper and the RLC lower layer, which allows access to feedback from MAC layer. With this, the 5G NR mmWave development platform is incorporated

¹Derived from NFV MANO defined by the European Telecommunications Standards Institute (ETSI) [27], which describes a standardized architecture for managing and orchestrating VNFs.

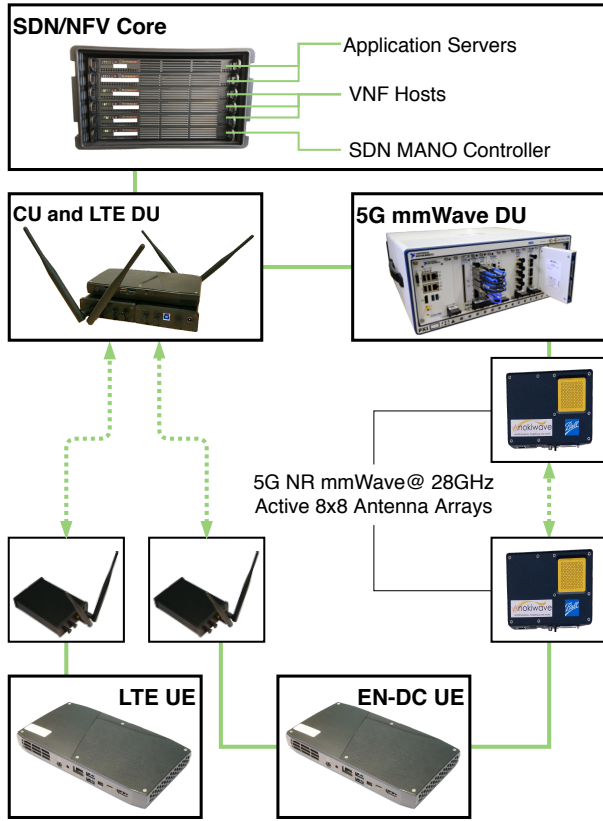


Fig. 4. Experimental setup illustrating the used hardware components. A set of general purpose hosts runs the measurement applications, the SDN MANO controller as well as virtual CN functionalities. While the LTE UE only connects with the LTE DU, the EN-DC UE is capable of additionally connecting via 5G NR to the 5G mmWave DU.

as additional DU via a joint X2/F1 interface similar to the 5G NSA operation mode (cf. Figure 1) and the CU-DU split as proposed in [26]. The implemented split unit is capable of handling prioritization and distribution rules received from our SDN MANO controller, which in turn also impacts the public data network (PDN) gateway to ensure QoS by integrating network slicing at both core network and RAN level.

The experimental laboratory setup is illustrated in Figure 4, for details also refer to Table II. At the top, a set of general purpose hosts runs virtual CN functionalities, the SDN MANO controller and the measurement applications. The used measurement application is *iperf 2.0.10* and is executed on *ubuntu 18.04 lts* systems, whereas the SDN MANO controller manages the different application traffic flows and overall resource utilization. Its implementation is based on *ryu 4.3* (cf. our previous work [7]), while the open source software *openvswitch 2.9.2* serves as SDN-enabled network switch. All general purpose hosts are time-synchronized via the precision time protocol (PTP) to ensure highly precise, cross-device delay measurements.

Our extended *tinyLTE* system implements the described functional split as well as the E-UTRA-NR dual connectivity (EN-DC). The CU and the LTE DU part utilize hardware components as in [6], and the 5G NR DU is represented

by the connected mmWave transceiver system [24]. At the bottom, two end devices execute applications with one device being capable of E-UTRA-NR dual connectivity (EN-DC), i.e. it may use the 5G NR mmWave link in addition to the legacy one via LTE. (The UE part of mmWave SDR system is omitted to enhance clarity of the illustration.) For the mmWave communication link, 5G active antenna arrays as described in [28] are used to provide the essential high gain, high directivity pencil beams at 28 GHz. Throughout the subsequent measurements, undisturbed radio channels are assumed, as this work focuses on the holistic system concept and appropriate reactions to changes in the condition of the radio channels are presupposed to be handled by lower layers.

B. Test Sequence and Illustrative Measurement Result

We test the system by repeatedly executing a predefined traffic sequence as shown in Figure 5: Starting with the initial phase, the 5G NR mmWave capable device operates a prioritized application e.g. a control link for a remotely operated UAV. This high priority application introduces QoS constraints regarding a maximum delay and a required data rate. After 10 s (Phase II), the same user equipment (UE) starts a monitoring application, e.g. streaming low priority telemetry data, on a best effort (BE) traffic flow requiring no guaranteed availability, throughput, latency or reliability. The second UE, the conventional LTE-only device, starts another, similar BE application at the beginning of the third phase (20 s). Since the total demanded data rate of the two BE streams exceeds the available resources, the second UE acts as competitor on the LTE side. During this experiment, we analyze downlink transmissions only, so the responsibility for ensuring QoS lies solely within the operator part of the mobile network.

Figure 6 shows the course of data rate and delay of the applications over time during one exemplary measurement run. Both values are normalized to the case of an ideal, exclusive operation of each single application to stress the comparability of the highly different air interfaces of 5G NR mmWave and conventional LTE. The prioritized application running on its dedicated, privileged slice over the 5G mmWave DU continuously maintains sufficient data rates and delays independent of other applications throughout the complete test sequence. A starting best effort application is served by a lower priority slice utilizing the LTE link. Due to the initially

TABLE II
DISTRIBUTION OF THE INDIVIDUAL FUNCTIONS ON THE USED HARDWARE

Hardware Entity	Function
general purpose host #1	Application: iperf source #1 and #2
general purpose host #2	Application: iperf source #3, PTP master
general purpose host #3	SDN MANO ctrl., VNFs of core network
general purpose host #4	Base station CU, LTE DU
general purpose host #5	EN-DC UE, iperf sink #1 and #2
general purpose host #6	LTE UE, iperf sink #3
general purpose hosts #1-6	time-synchronized via PTP
SDR device #1	Radio front end of LTE DU
SDR device #2	Radio front end of LTE UE
SDR device #3	Radio front end of EN-DC UE
mmWave SDR System #1	5G mmWave DU
mmWave SDR System #2	5G NR module of EN-DC UE

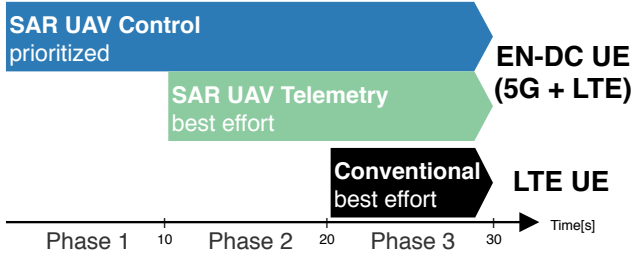


Fig. 5. Test sequence definition by reference to exemplary applications used for subsequent measurements: While the prioritized, throughput and delay constrained application runs throughout the complete measurement run, a BE application starts after 10s at the same, dual connectivity capable device and another BE application follows on a legacy device after 20s.

exclusive use of this link in phase 2, the data rate and delay of this best effort traffic start out at the respective ideal level. With another best effort application also attaching to the LTE DU in phase 3 (Label A), the delay increases by a factor of almost 20 due to the competition of two best effort applications saturating their shared network slice. This saturation becomes clear once again at the halving of the data rate during the third phase. Owing to the measurement setup, increased data rates and decreased delays are displayed again when the applications are shut down at B due to averaging over time intervals and asynchronous exiting of the different host applications.

In conclusion, the prioritized application experiences consistently unaffected data rates and delays, since it is served by another network slice and need not compete for resources.

Please note, that due to current interfacing constraints of the mmWave development platform, a reduced overall system capacity and an additional processing delay with a distinctive sawtooth-like behavior is introduced as a matter of principle. In this context the absolute values are neglected as they are not subject of this work. The adjustment of the mmWave platform's interface to allow for appropriate and more precise absolute values will be addressed in a subsequent work, where the exploitation of the full system capacity as well as the lowest systemic delay and an experimental evaluation of the system behavior at full load will be further investigated.

C. Statistical Evaluation

The above test sequence is repeated over 100 runs while the experimental setup records average metrics in 50 ms intervals to allow for a statistical evaluation of QoS fulfillment. The measurement results are illustrated as box plot diagrams in Figure 7. While the prioritized SAR UAV control application of the EN-DC UE is active during the complete sequence (phase 1 to 3, depicted by the leftmost column), the device's BE telemetry application starts at phase 2 and is exposed to competition in the third phase as shown in the second and third columns, respectively. The rightmost column shows the delay distribution of the BE application of the LTE UE, which is only started in phase 3. As exclusive application in phase 2 acquiring all resources from the LTE DU, the BE telemetry application achieves low delays. The outliers of the two BE applications (right three columns) are observed at the transition

from phase 2 to 3 as well as when the applications shut down at the end of the test sequence, indicated in Figure 6 as A and B.

However, with a competing BE application in phase 3, the delays of both rise sharply as also seen in Figure 6, whereas the delay of the privileged application remains unaffected due to the dedicated network slice within the aforementioned constraints regarding its absolute values. Hence, the functional split implementation and realized NFV/SDN-based core network slicing can be considered validated, since they enable a QoS compliant end-to-end communication network as proposed.

With the huge frequency spectrum availability at the mmWave domain (the current mmWave development plat-

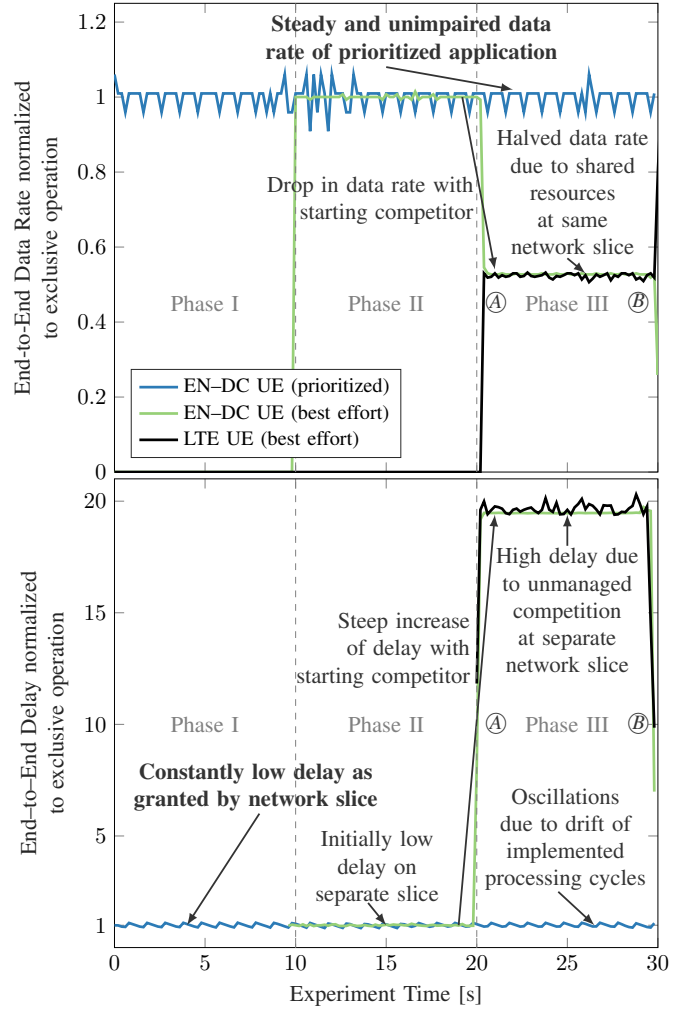


Fig. 6. Time series of exemplary test sequence of the different applications served by distinct network slices. While granting QoS to a high priority application, the low prioritized best effort applications are still supplied with residual resources, but suffer from lower data rates and substantially higher delays in phase 3 due to the intended unmanaged competition at their shared network slice. Please note that the data rate as well as the delay values are depicted normalized to the case of an ideal, exclusive operation to emphasize the contrast between the QoS aware prioritization and the impairment of miscellaneous applications. Since the inclusion of the 5G mmWave development platform currently does not match our objective due to the underlying implementation, a stressable comparison of the absolute values is not subject of this work.

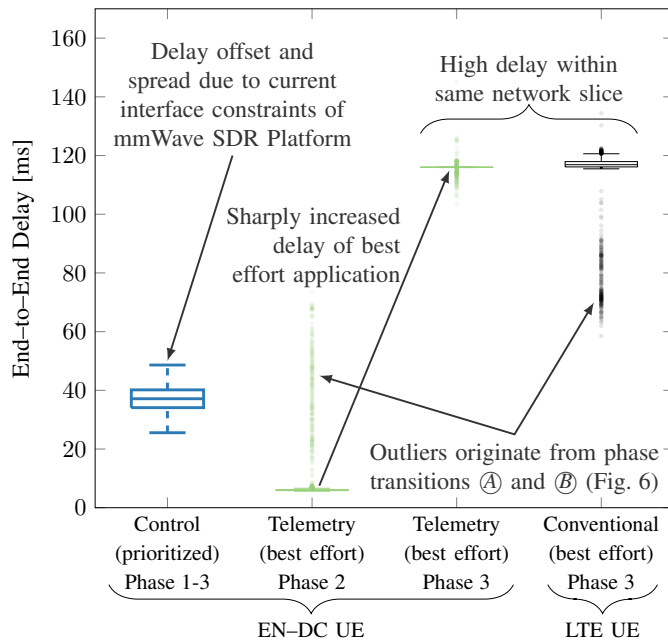


Fig. 7. Statistical analysis of delay measurements. While the telemetry application suffers from sharply escalated delays, the delay of the prioritized control application remains at almost the same level among all measurements. Please note, that its offset and the higher deviation compared to the telemetry link in the second phase are introduced by current interfacing constraints of the used mmWave SDR development platform as a matter of principle and will be addressed in future work.

form utilizes a bandwidth of 800 MHz) and the high spatial frequency reuse capability due to the focused and flexible directional radio pattern of the phased array antenna, it is believed that many demanding applications are able to be handled by the 5G mmWave link simultaneously without reaching the system boundary.

D. Considerations on the System's Extensibility

As an outlook on the extensibility of the proposed system with regard to further DUs, a baseline measurement of the overall system delay is conducted considering a virtual, bridged DU, since it allows for an evaluation of the core network components' performance. A mean delay of 4.66 ms with a standard deviation of 160.7 μ s can be observed.

In summary, results suggest that the proposed software-defined end-to-end network slicing architecture is capable of realizing communication links for QoS applications especially demanding continuously low delays and consistently high data rates. To further portray real world conditions, additional delays and various constraints may be emulated by adjusting the processing and link performances of the individual components as well as the complete system.

V. CONCLUSION

While the fifth generation of mobile communication features vast performance improvements compared to LTE, some necessary but breaking changes are introduced in the core and radio access networks, which in turn motivates a transition phase based on the fourth generation core. Our proposed

system shows how end-to-end slicing and QoS guarantees can be enabled in this intermediate state by means of software-defined networking and additional logic in the base stations.

We implement these ideas in a research platform comprising new radio and open-source LTE infrastructure. Virtualized components increase the platform's flexibility and allow for virtual network separation. An application scenario with a privileged traffic flow ensuring QoS and additional, competing flows demanding resources in a best effort manner is analyzed. The results indicate that QoS awareness can reliably maintain a traffic flow unaffected throughout the complete measurement series. The proposed architecture even allows for further extensions like the inclusion of additional distributed units of the same as well as external radio access technologies.

Future work will use the system introduced here to perform further investigations into the benefits and potential issues of the transition towards 5G and beyond. Among others, user mobility will be evaluated in a next step, since it is believed to be especially challenging for granting QoS via mmWave links.

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