García-Avilés, Ginés; Gramaglia, Marco; Serrano, Pablo; Banchs, Albert. POSENS: a practical open source solution for end-to-end network slicing, in: *IEEE Wireless Communications*, 25(5), November 2018, pp. 30-37

DOI: https://doi.org/10.1109/MWC.2018.1800050

POSENS: a practical open-source solution for end-to-end network slicing

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***Abstract*—Network slicing represents a new paradigm to operate mobile networks. With network slicing, the underlying infrastructure is "sliced" into logically separate networks which can be customized to the specific needs of their tenant. Hand-on experiments on this technology are essential to understand its benefits and limits, and to validate the design and deployment choices. While some network slicing prototypes have been built for the radio access networks (RANs), leveraging on the wide availability of radio hardware and open source software, there is currently no open source suite for end-to-end network slicing available to the research community. In this paper we fill this gap by developing an end-to-end network slicing protocol stack, POSENS, which relies on a slice-aware shared RAN solution. We design the required algorithms and protocols, and provide a full implementation leveraging on state-of-the-art software components. We validate the effectiveness of POSENS in achieving tenant isolation and network slices customization, showing that no price in performance is paid to this end. We believe that our tool will prove very useful to researchers and practitioners working on this novel architectural paradigm.**

I. Introduction

5G Networks will change the way in which cellular connectivity is provided. High data rates (50+ Mbps), extensive coverage (10+ Tbps/Km^2) and low latencies (<5 ms) are just few of the target Key Performance Indicators (KPIs) to be fulfilled by the next generation mobile networks [1]. However, not all services are going to require these KPIs, as different applications will have different requirements. To efficiently provide services that meet these requirements, one key enabling technology is *network slicing* [2].

A *network slice* consists of a set of resources assigned to a *tenant* to provide a specific *service*.[1] Those resources are both network resources (e.g., spectrum, link capacities), and cloud resources (i.e., the infrastructure required to run the Virtual Network Functions, VNFs). Tenants could be mobile network operators providing enhanced Mobile Broadband (eMBB), or third party *verticals* [3] that use a slice specifically tailored to their needs (e.g., ultra-low latency). To satisfy the service requirements of each tenant, a different network slice will be instantiated to provide the corresponding service. This ability to provide highly customizable services over the same shared infrastructure will increase the revenue opportunities, and drastically reduce the costs of 5G networking, due to the improvements in efficiency.

The advantages of network slicing are clear [4], and there is a wide consensus among the industrial and standardization communities on the need to adopt this technology. However, we lack a thorough experimental validation of its effectiveness, e.g., on the gains when using different mechanisms for orchestrations, or under different traffic scenarios. While there are implementations for some of the the enablers for network slicing, to the best of our knowledge there is no solution that implements end-to-end network slicing. More specifically, virtualization is a mature technology that has been extensively used for the wired elements, with technologies such as e.g. OpenStack[2] and Kubernetes[3] for virtual machine and containers management, respectively. However, the situation is less mature for the wireless access part, Orion [8] being among the few proposals to implement slicing at the Radio Access Network (RAN) that have been tested in practice.

In this paper, we fill this gap with the design of POSENS, a practical open-source solution for end-to-end network slicing that comprises all the elements of an end-to-end mobile network: the User Equipment, the RAN and the Core Network. POSENS implements a "slice-aware shared RAN" solution, enabling the effective and efficient sharing of the network resources between different tenants that can independently provide different services.

While POSENS is based on state-of-the-art open-source solutions for mobile networks, these are substantially extended with the following additional implementations: *(i)* a multi-slice UE, *(ii)* a slice-aware shared RAN solution, and *(iii)* specific multi-slice Management and Orchestration (MANO) capabilities, all of which are needed to provide an end-to-end solution for network slicing.

POSENS provides a complete solution to instantiate end-to-end slices, using commodity hardware and Software Defined-Radio (SDR) boards for development. Our results show that it supports the efficient instantiation of independent, customizable network slices. This open-source solution is available[4] for developers to put their slicing ideas in practice. This tool will thus support researchers and practitioners experimenting with different algorithms and mechanisms for network slicing. The codebase includes the most important network elements and the MANO part. POSENS can run on any compliant physical hardware, independently of the deployed transport network.

The rest of this paper is organized as follows. Section II provides a discussion on the building blocks needed to implement the network slicing concept, including a review of open-source software projects in the field of virtualized wireless

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[1] In this paper, we will use irrespectively the terms slice, tenant and service.

[2] https://www.openstack.org

[3] https://kubernetes.io

[4] The source code and detailed installation guidelines are available at https://github.com/wnlUC3M/

mobile networking. We describe the design of POSENS in Section III, and validate its efficiency in providing isolation across slices in Section IV. Finally, Section V concludes the paper.

II. The path towards end-to-end network slicing

Network slicing can be seen as a consequence of the *softwarization* of the protocol stack. We next review the path towards this softwarization, highlighting the complexity involved with sharing RAN resource across tenants due to the tight synchronisation required. Then, we review different approaches to share the RAN, each one imposing a different trade-off between efficiency and isolation. Finally, we review the most promising software solutions to instantiate a mobile network, identifying the building blocks for the design and implementation of POSENS.

A. Softwarization of networks

4G and previous networks are usually composed of monolithic physical boxes, each one providing a very specific functionality and running specialised software on specialised hardware. 5G and future networks will be based on network function virtualization (NFV) and software defined networking (SDN), these technologies enabling flexible network deployments thanks to *network programmability*.[5]

In this new approach, a network is decomposed into three layers: *(i)* infrastructure, which consists in general-purpose hardware (e.g., cloud computing servers), *(ii)* network, composed by all the networking functions, virtual (VNFs) or physical (PNFs), and *(iii)* management and orchestration, that extends the legacy management layer (e.g., the Element Managers defined by 3GPP) to support the instantiation and orchestration of network functions.

This approach is represented in Fig. 1, which illustrates one configuration of the testbed that we use to validate POSENS, where the same User Equipment (UE, in POSENS a "Multi-Slice UE") runs two independent slices (blue and red) over the same set of physical resources. The infrastructure layer is composed by a laptop, two SDR cards (USRP B210 boards) that provide the RF front end, and a small set of server nodes. The network layer runs over this infrastructure, and is composed of the required network functions such as the RAN, HSS, S/P-GW.[6] Finally, the management and orchestration also runs over the same infrastructure, and is in charge of instantiating and connecting the networking functions composing the slices.

To support the above vision, data from different slices (and not necessarily from different UEs) has to be (de)multiplexed over a set of shared resources. That is, the mobile network protocol stack has to be divided into VNFs that explicitly belong to one tenant (i.e., usually the core network), and functions that are shared across them (i.e, usually the access network, to lower the deployment costs). This imposes some novel requirements on various elements, in particular, on the RAN functions to support e.g., the existence of multiple Core Networks (CNs), or for the UE to attach to multiple slices at the same time. Allowing UEs to simultaneously access different slices is essential for many scenarios envisioned in 5G, including the simultaneous access to services supported by different slices as well as the provisioning of a service that employs multiple slices. For instance, for "Industry 4.0" scenarios, augmented reality devices could connect to an "industrial" slice and to an enhanced mobile broadband slice; for vehicular scenarios, different slices could be used for automated driving and for infotainment services. This is in line with the 3GPP SA2 standardization work, which envisions a 5G core network that can attach to up to 8 network slices instances at the same time. This multi-slice support requires that traffic from different tenants has to be handled over the same spectrum, which makes it more complex to have dedicated/customized RANs for different slices. In what follows, we discuss how to perform RAN slicing from an architectural point of view.

B. Addressing the RAN slicing

We next present the three architectural options that have been proposed in the literature [4] for RAN Network Slicing. These options are presented in order of "increasing depth" in Fig. 2, where the deeper the slicing (the "MUX" block represents this depth), the less functions are shared by different tenants.

The leftmost option ("Option 1") is the so-called **slice-aware shared RAN**, which basically consists in sharing the complete RAN, and then each tenant is responsible for its CN. With this option, the same UE can use different slices, and therefore connect to different CNs. This solution, which can be considered as the "basic" solution to support network slicing, provides relatively little isolation across tenants, but also leads to the highest potential gains in terms of efficiency. This solution can be related with some current proposals such as 3GPP LTE eDECOR [10], introduced to support the instantiation of dedicated CNs. However, eDECOR requires introducing changes to the CN and new signaling messages for the connection setup (something that POSENS does not). We also remark that 3GPP RAN3 Working Group [11] is considering a functional split performed at this level. This approach nicely fits with the shared RAN slicing option, in which multiple network slices are handled by a centralized unit. While with this option the RAN is shared to a large extent by different slices, the core instances are completely independent among tenants, allowing per-tenant configuration, orchestration and (cloud) resource assignment.

The central option in the figure ("Option 2") is the **slice-specific Radio Bearer** configuration. With this option, the slicing goes deeper in the network stack, and basically only cell-specific functionality are shared, i.e., the PHY and MAC layers in the user plane, and the RRC in the control plane. This configuration increases the resource isolation between tenants, at the price of a higher complexity at the MAC layer (for instance, to fully exploit this resource isolation, slice-aware scheduling algorithms are required).

[5] In fact, one of the most relevant features of future 5G Networks is to reduce the time needed to deploy a new service from 90 minutes to 90 seconds.

[6] In POSENS we use LTE/EPC VNFs as they are currently the only open-source option available. However, POSENS may easily integrate other 5G VNFs, especially the ones related to the CN.

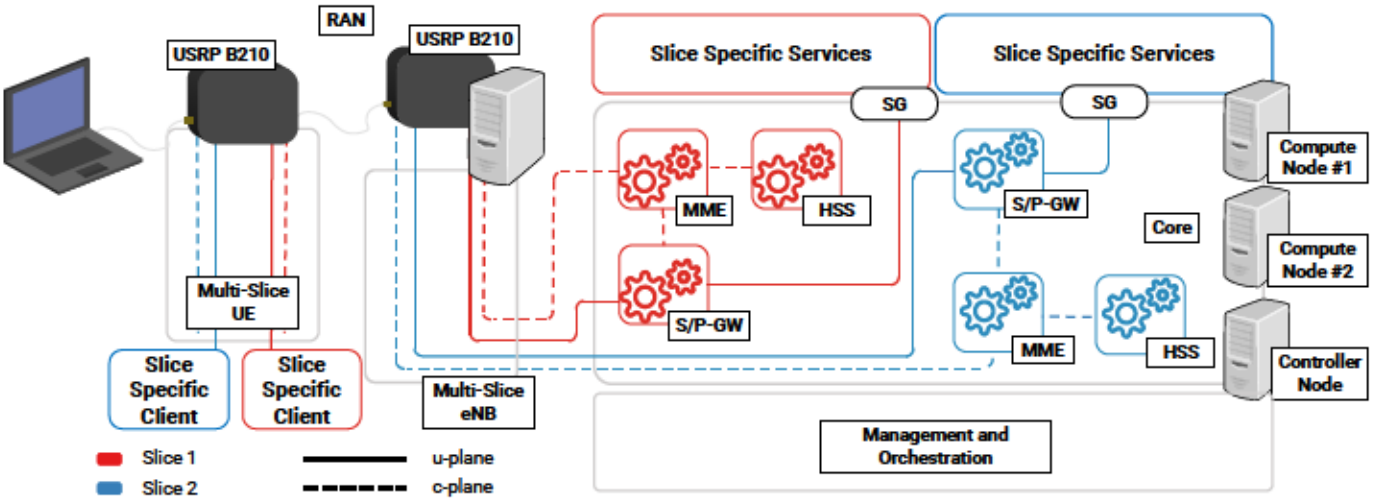


Fig. 1: A multi-slice network architecture. We also used this *blueprint* for the evaluation of POSENS.

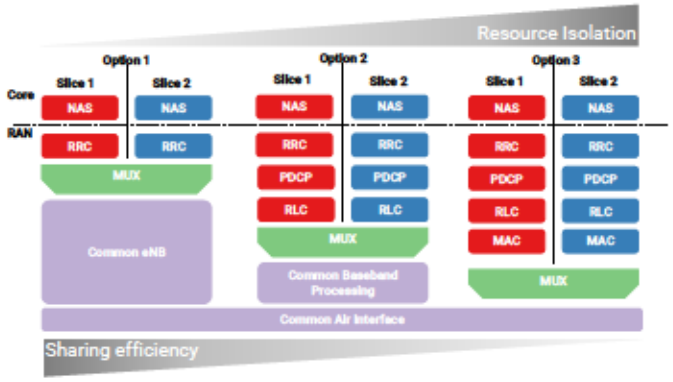


Fig. 2: Different RAN slicing options.

Finally, the last option ("Option 3") is the so-called **slice-specific RAN**. In this case, only the air interface is shared among network slices, while all the other functionality is instantiated specifically for each tenant. This configuration provides the maximum degree of freedom, given that each network slice can be customized down to the physical layer. However, this option also requires a tight synchronization between the multi-tenancy policies implemented by a common part, and the per-slice (dedicated) implementation.

This option could be particularly useful in scenarios where different radio access technologies coexist within the same shared spectrum, e.g., 4G and 5G. Since it may be very challenging to dynamically reallocate spectrum resources at a fine time granularity, this option may potentially harm resource utilization and limit the potential multiplexing gains.

The above options can be regarded as a "roadmap" to enable a fully configurable protocol stack to support any network slicing option, where each option presents a different trade-off between efficiency, isolation and complexity. For the first release of POSENS, we decided to implement "Option 1," which can bring the maximum efficiency gains and provides end- to-end slicing, in this way providing researchers with a tool to experiment with different algorithms and mechanisms. Although options 2 and 3 provide a higher degree of isolation between slices, "Option 1" already enables key features without requiring the complexity of more advanced RAN schema.[7] More specifically, this option readily supports experimentation on fundamental research items in 5G, such as *(i)* per-tenant Service Function Chaining (SFC), as the network slices flows go through chains that contains instantiations of different VNFs, or *(ii)* per-tenant orchestration, as different tenants can implement their own MANO using their preferred software on their cloud, enforcing thus service specific management and orchestration policies regardless of other tenants' ones.

C. Software building blocks

There are several recent initiatives to prototype mobile networks in software, with most solutions building on the GNU Radio development suite and the Ettus Research USRP SDR platforms, and running on standard Linux-based computing equipment (Intel x86 PC architectures).[8] We next provide a short review of the current ecosystem of open solutions.

Concerning **the RAN part**, three of the most popular SW solutions to run LTE over SDR are Eurecom's OpenAirInterface (OAI),[9] openLTE,[10] and srsLTE.[11] OAI [12] provides an implementation of a subset of LTE Release 10 elements, including the UE and the eNB. Its performance is considered relatively good, although is also acknowledged that the code structure is complex and difficult to customize. It is also worth mentioning that the eNB and UE RAN are licensed under a specific OAI Public License.

[7]While Options 2 and 3 require very tight synchronization among slices, this is not an issue for Option 1 since it employs a conventional RAN stack that already provides the required synchronization.

[8]We note that there are complete commercial products such as the Amari LTE 100 (a fully softwarebased LTE BS solution), its closed license makes it unsuitable for research activities.

[9]http://www.openairinterface.org/

[10]http://openlte.sourceforge.net/

[11]https://github.com/srsLTE/srsLTE

openLTE is an open-source project providing an implementation of LTE specifications, which includes a C library, Octave code for testing downlink and uplink physical random access channel (PRACH) functionalities, GNU Radio applications for DL functionalities, both simulated and using HW platforms, and a simple implementation of an eNB using USRP. While its code is considered as relatively well organized, documented and would result easier to modify, it does not provide an UE, and many features are still unstable or under development.

Finally, the srsLTE [13] open-source project provides a platform for LTE Release 8 experimentation, designed for maximum modularity. The RAN part provides a complete UE application and a complete eNodeB application. The project is more recent than OAI, and in general the source code is considered easy to customize, although it also consumes more CPU resources than the other alternatives. The code is provided under an AGPL v3.0 license.

Given that our aim is to develop a solution to validate end-to-end slicing, and not an efficient software to put in production, code modularity and re-usability are determinant factors when selecting a platform, and therefore we decided to design our solution as an extension of the srsUE and the srsENB (the applications for the UE and eNodeB, respectively).

We were convinced by the srsUE source code availability, as having a stable UE software implementation is beneficial for several reasons, e.g., it supports the development of multi-slice inside the UE, and speeds up the deployment and testing of new orchestration solutions.

Concerning **the core network**, apart from commercial solutions such as OpenEPC[12] (also supporting shared source code licensing), two of the most relevant solutions are the ones associated with the same initiatives mentioned above. Firstly, srsLTE has very recently released srsEPC, a light-weight CN implementation, including the mobility management entity (MME), home subscriber server (HSS), packet and serving gateways (P-GW and S-GW, respectively), under the same license. Secondly, OAI also provides the same elements for a basic EPC solution, in this case released under a standard Apache v2.0 license. Given that when we started our work only the latter was available, we used OAI CN as the software solution for the CN.

One additional advantage of our POSENS, which contrasts eDECOR (see Section II-B) is interoperability: our solution works with any implementation supporting the S1AP protocol (we confirmed that POSENS is compatible with different different commercial EPCs, whose names we cannot disclosure due to confidentiality agreements).

Finally, concerning **MANO**, it has received a lot of attention from both the open-source community and the enterprises [14]. There is a wide range of fully-fledged MANO tools such as Open Baton,[13] Open-O[14] or OSM,[15] that provide the required functionalities related to the VNF life-cycle management, including their scaling on a virtual infrastructure. They rely on a Virtual Infrastructure Manager (VIM), a software that is more mature, as it has been already employed in production cloud computing environments since many years. Among VIMs, we can list solutions such as OpenStack[16] or OPNFV.[17] However, as key required features such as per-tenant orchestration are not available with existing open-source solutions, we decided to implement POSENS MANO using a dedicated software that directly leverages on the VIM APIs.

We finish this section by reviewing state-of-the-art solutions on Network Slicing that have recently appeared, which we list in Table I. To the best of our knowledge, POSENS is the most complete solution as it includes an open-source, end to end, network slicing-aware mobile network stack, that includes also a Management and Orchestration framework. Other solutions are either considering the RAN only [5], [6], [7] or neglecting the UE role [8]. Furthermore, POSENS is the only completely open-source solution that is readily available in a public repository (GitHub).

III. Design of POSENS

POSENS provides an implementation of all the modules needed for an end-to-end network slicing-aware mobile network. This includes elements belonging to all the realms of a mobile network (UE, RAN and CN), plus an orchestration framework. Still, the most important enabler of an end-to-end network slicing setup is RAN slicing.

In the following, we describe the design of our solution to support RAN slicing. This solution consists on introducing a number of changes and new modules to the srsLTE UE and eNB implementations. The resulting software architecture, for the case of two slices, is illustrated in Fig. 3, where each slice is depicted with a different color (we consider the case of two slices for simplicity, but the software can be easily extended to support more slices). We will also assume for simplicity that each slice is associated with a different tenant.

As discussed in Section II, we decided to implement in our first release of POSENS the "Option 1" for RAN slicing, where slices are multiplexed and demultiplexed at the PDCP layer. This option has the additional advantage of requiring less changes in the eNB software implementation, which is the main cause of instabilities in a SDR-based testbed. The cornerstones of the solution are the "slice coalescer" modules, located at the PDCP layer and above. These modules forwarding the control and data layer information for each slice over the common communication channel. Another key feature of our implementation is that each slice at the UE has its own RRC module, and does not require any additional functionality inside the CN. Conversely, at the eNB there is only one RRC module, as with its default behavior is capable of managing multiple Non-access stratum (NAS) from various users simultaneously. In what follows, we provide a more detailed description of the enhancements required by our solution, by describing the behavior of the UE and the eNB.

A. User Equipment

The UE plays a fundamental role in the network slice selection procedure. As depicted in Fig. 3, one slice performs

[12] https://www.openepc.com
[13] https://openbaton.github.io/
[14] https://wiki.open-o.org/
[15] https://osm.etsi.org/
[16] https://www.openstack.org
[17] https://www.opnfv.org/

TABLE I: Recent software contributions for network slicing.

Work	Base Software	Main purpose	Main Feature	Limitations	Open Source
Mendes et al. [5]	srsLTE	RAN Slicing	Multiple, per tenant, eNB virtualization	Implementation only up to MAC layer.	No
Chang et al. [6]	OAI	RAN Slicing	Thorough evaluation of slices utilization	RAN Slicing only.	No
Foukas et al. [7]	OAI	RAN Slicing	SDN-based RAN slicing	It does not include a core.	Download upon request
Foukas et al. [8]	OAI	End-to-end slicing	Core Network handling multiple slices	Single Slice UE only.	No
POSENS	srsLTE	End-to-end slicing	Slice aware shared RAN.	One RAN split available.	Yes

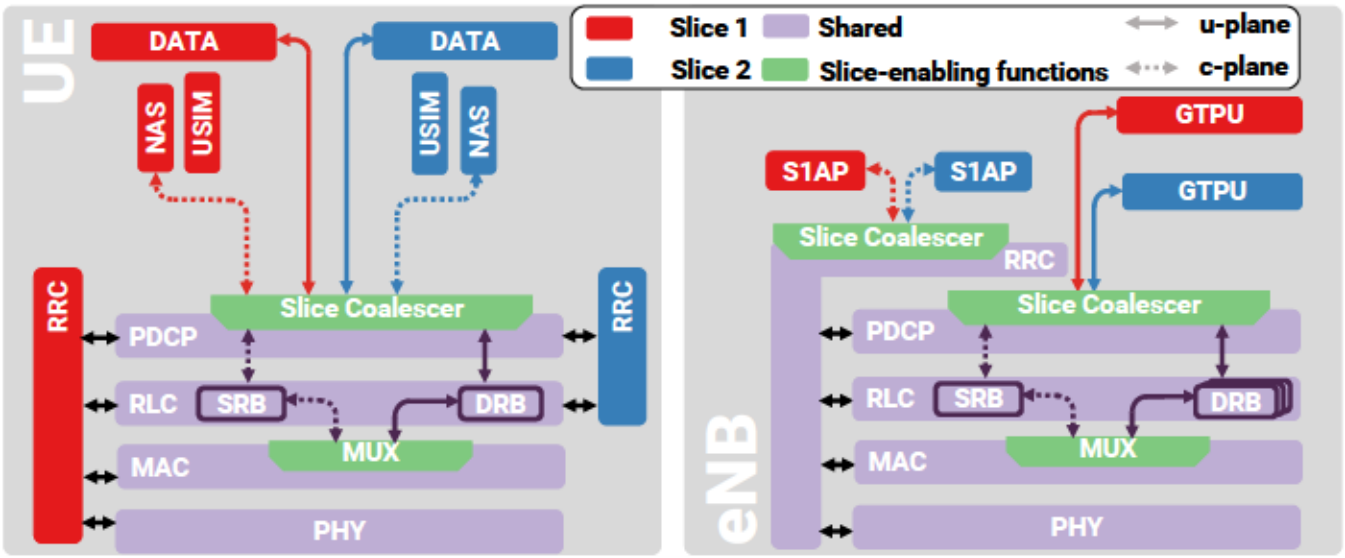


Fig. 3: Design of POSENS: changes introduced at the UE and the eNodeB.

a full radio configuration of all the RAN layers (including PHY and MAC), while the other one relies on the RRC configuration parameters set by the first slice and prepares the PDCP entities and the RLC channel managers (Acknowledged mode for the u-plane and Transparent mode for signaling messages).

Once the UE has been powered on, the (unmodified) PHY performs the usual cell search (following the configuration provided within the MIB, SIB0, SIB1 and SIB2 messages) and synchronization. Then, the RRC module corresponding to the first slice sets up the initial connection with the eNB by performing the Random-Access procedure (RA) to get an initial UL grant, i.e., a valid configuration for PDCP, RLC, MAC and PHY. This configuration is shared across slices, and therefore subsequent RRC modules (corresponding to other slices) will not request it. This motivates that the `RRCConnectionSetup` message that arrives during the RA process has to be stored within the PDCP module, for subsequent slices to be able to establish their session with the CN.

Following the initial UL grant, the NAS protocol of the first slice establishes a session with the CN, generating a `RRCConnectionSetupComplete` message nesting the initial NAS messages in the same packet. The selection of different slices happens in a sequential fashion, after the first slice RRC has configured the wireless link, the subsequent slices are configured using the reception of a `RRCConnectionSetupComplete` as triggering event.

That is, upon a `RRCConnectionSetupComplete` the PDCP sends to the next slice a previously stored `RRCConnectionSetup` message, containing the details of the RRC channel. This, in turn, triggers the NAS authentication procedure in the new slice. Each time a slice finishes its NAS configuration, the RRC calls a `slice_configured` function within the PDCP, including the `(slice_id, IP address)` tuple of the slice, which will support the proper forwarding of information within the module (this is only needed for receiving information).

Besides coordinating the c-plane, the slice coalescer in the UE also has to multiplex and demultiplex the u-plane. This is achieved by exploiting the data multiplexer available at the MAC for the uplink:

this function demultiplexes the data coming from the lower layers and forwards to the appropriate slice instance at the PDCP on a per-destination IP prefix basis.

B. eNodeB

The changes in the eNB are the counterpart of the ones introduced in the UE. That is, the slice coalescer handles the multiplexing and demultiplexing of the c- and u-plane. The multi-slice updates in the eNB are less elaborated than the ones in the UE, as the eNB is already capable of handling parallel authentications coming from different UEs. We remark that multiple authentications coming from the same multi-slice UE

(such as the one described in Section III-A) can be considered as atomic operations, as they happen sequentially.

This simplifies the required enhancements at the eNB, as there are no concurrent NAS procedures for the same UE running simultaneously, and therefore each one can use the same inner data structure available at the RRC. In this way, we use a flag to mark the slice under configuration, which enables forwarding the control traffic to the corresponding CN via the appropriate S1AP interface.

Like with the UE implementation, the u-plane multiplexing happens in the PDCP, following an IP-prefix matching approach, i.e., data traffic is forwarded to the right CN by considering the source address of IP packets.

C. Core and MANO

The main enabler of our slicing solution is the RAN slicing. Therefore, to allow an easier experimentation with unmodified software solutions, we did not tackle CN VNFs, leveraging on a vanilla implementation such as the one provided in the OpenAirInterface suite. Similar considerations hold for the MANO part: one of our objectives is to allow the open experimentation of MANO algorithms on top of the `POSENS` stack.

The MANO of VNFs, a fundamental part of the future 5G Networks, is being standardized by the 3GPP SA5 and will leverage on the already consolidated elements of the ETSI NFV MANO architecture [15]. We include in `POSENS` a baseline implementation of this MANO functionality, which builds on top of a open source VIM (OpenStack), and provides a per-slice orchestration (which is the functional role played by the VNF Manager and the NFV Orchestrator in the ETSI architecture) through an ad-hoc Java software. This implementation leverages directly on the Nova and Neutron APIs to provide a lightweight version of the VNFM-Vi and Or-Vi reference points defined by ETSI.

IV. Evaluation

We next validate and evaluate our solution by deploying a small testbed consisting of one UE implementing two slices, and one eNB connected to two different CN (one per slice). The testbed architecture is depicted in Figure 1. The UE runs over an Ettus USRP B210 board connected to an HP OMEN laptop, running Ubuntu Linux 16.04. The eNB runs over another B210 board, connected to a Intel NUC running the same Linux distribution. The TX and RX ports of one B210 board are connected to the RX and TX ports, respectively, of the other board, using coaxial cables with SMC connectors to prevent any interference. To implement the CN, we run two instances of the OAI CN implementation, which contains the MME, HSS, S-GW, and P-GW. The OAI-CN VNFs are packaged in Ubuntu 16.04 VM, running in an OpenStack managed cloud composed of three compute nodes and one controller node.

Before performing the actual validation of `POSENS`, we first conduct an extensive evaluation of the best RAN (i.e., srsLTE) parameters that lead to the most reliable configuration. To find a good trade-off between RAN performance (in terms of throughput) and stability, we set the channel bandwidth to 10 MHz and a RX gain of 60 dB for the UE and 60 dB for the eNB. We used the LTE channel 7 (centered around 2600 MHz).

A. Independence between slices

We first validate that the slices can run simultaneously and independently, in this way supporting e.g., experimentation in scenarios with multiple slices, each one potentially reconfigured in real-time. To this aim, the experiment starts with two configured slices, each one implementing a periodic request- response service between the UE and a server. We emulate that these servers are relatively far away by introducing an extra delay of 100 ms via the `tc` command. Then, after 20 s, the server of the second slice is moved to the eNB, simulating e.g. the use of a MEC-like solution. We represent the obtained performance in terms of average Round Trip Times (RTTs) across 10 repetitions in Fig. 4a.

As the figure illustrates, at the beginning of the experiment both slices experience the same RTT of approx. 120 ms, with a few outliers across experiments. The re-allocation of the server in the second slice has an obvious impact on performance, with the RTTs immediately reduced to approx. 20 ms, while the performance with the first slice remains unaltered. With this experiment, we thus confirm that researchers could prototype scenarios where different services are provided with different slices, and each service could be independently modified without altering the others.

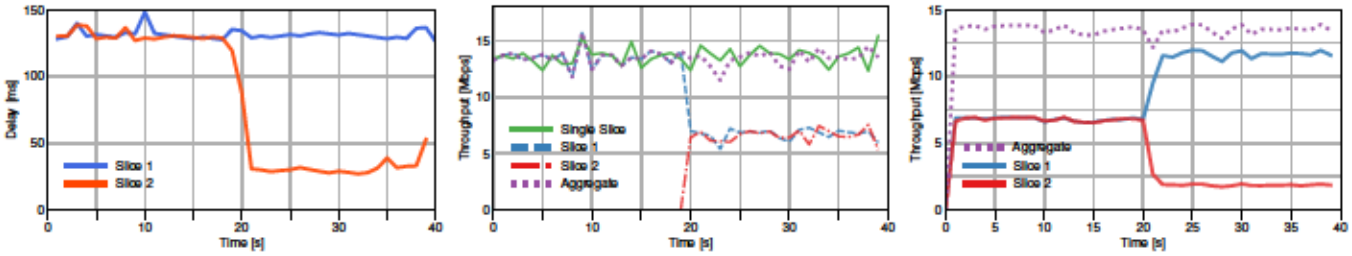
B. Throughput performance

We next assess quantitatively the performance of our solution, to analyze if the overall efficiency is degraded because of the use of slicing, and if the slices are fairly sharing the available resources. To this aim, we start our experiment with both slices configured, but only one (“Slice 1”) performing a TCP download from a server. Then, after 20 s, another download is performed on the second slice (“Slice 2”), from a different server. We illustrate the per-slice throughput and the total throughput (“Aggregated”) averaged over windows of 1 s in Fig. 4b. We also represent in the figure the throughput performance when no slicing is done, i.e., both the UE and the eNB use the vanilla version of srsLTE (“Single Slice”).

The figure illustrates two main results: first, there is practically no difference in total throughput between our implementation and the use of the vanilla version of srsLTE, which confirms the efficiency of the developed solution. Second, when both slices are active, they fairly share the medium, each one obtaining approximately 50% of the total throughput (we repeated the experiment several times and in all cases the performance was very similar).

C. Slice customization and orchestration

We next show how our solution supports a per-slice orchestration and customization of services, as well as the adjustment of the resources that a slice consumes. We demonstrate this capability by modifying in real-time the chain of VNFs that



(a) Independence between slices (b) Total and per-slice throughput performance (c) Independent Service Function Chaining

Fig. 4: POSENS evaluation experiments

build a service. In particular, we insert two additional user plane functions into an operating slice: a traffic shaper and a firewall. Our experiment works as follows. We start with two slices serving downlink traffic to the UE, fairly sharing the channel as illustrated in Fig. 4c. Then, after 20 s, we add into "Slice 2" a firewall function to block incoming connections and a traffic shaper function to limit the bandwidth to 2 Mbps. As the figure illustrates, the effect is immediate and "Slice 1" receives a higher throughput. We also confirmed that connections were blocked immediately. This shows that, even though the our slicing solution cannot allocate RAN resources directly, it can control the overall resource consumption (including RAN) as long as terminals employ some congestion-aware sending mechanism.

D. Compatibility with commercial equipment

In this section, we confirm that our solution is compatible with commercial equipment. To this aim, we perform a connectivity test using a Nexus-5 phone, equipped with a Sysmocom programmable SIM card.[18] To support this test, we slightly modified the hardware setup, attaching an antenna to the eNB SDR card, and using isolation hardware (Ramsey electronics shielded enclosures[19]) to prevent interference.

We confirmed that POSENS supports both modified UEs and commercial UEs, namely, slice-aware and slice-unaware UEs. In this way, we support scenarios where several UEs can be attached to the same slice (e.g., eMBB), and only a few UEs, in need of specific services, require the instantiation of a different slice (e.g., an URLLC service). This further extends the applicability of our solution, opening it to a very wide range of testing scenarios.

V. Conclusions

We have presented POSENS, an open-source solution for practical end-to-end network slicing based on slice-aware shared RAN. This tool includes all the software components needed to deploy a multi-slice network setup. POSENS enables the slicing of the RAN as well as the core, which are fundamental building blocks for achieving end-to-end network slicing. We validated POSENS in a lab deployment, showing how it can obtain per-slice customization without paying a price in terms of performance. Our ultimate goal is to provide a tool that allows researchers and practitioners to experiment with per-tenant MANO algorithms, using the now widely available SDR and cloud hardware commodities.

[18]http://shop.sysmocom.de/products/sysmousim-sjs1

[19]http://www.ramseyelectronics.com/product_list.php?category=1&series=1

Acknowledgements

This work has been performed in the framework of the H2020-ICT-2014-2 project 5G NORMA (Grant Agreement No. 671584) and within the 5G-MoNArch project, part of the Phase II of the 5th Generation Public Private Partnership (5G-PPP) program partially funded by the European Commission within the Horizon 2020 Framework Program.

References

[1] D. Bega, M. Gramaglia, C. J. Bernardos Cano, A. Banchs, X. Costa-Perez, *"Toward the network of the future: From enabling technologies to 5G concepts,"* in Transaction on Emerging Telecommunications Technology, 2017.

[2] I. Afolabi, T. Taleb, K. Samdanis, A. Ksentini and H. Flinck, *"Network Slicing & Softwarization: A Survey on Principles, Enabling Technologies & Solutions," in IEEE Communications Surveys & Tutorials, 2018.*

[3] K. Samdanis, X. Costa-Perez and V. Sciancalepore, *"From network sharing to multi-tenancy: The 5G network slice broker,"* in IEEE Communications Magazine, vol. 54, no. 7, pp. 32-39, July 2016.

[4] P. Rost *et al.*, *"Network Slicing to Enable Scalability and Flexibility in 5G Mobile Networks,"* in IEEE Communications Magazine, vol. 55, no. 5, pp. 72-79, May 2017.

[5] J. Mendes, X. Jiao, A. Garcia-Saavedra, F. Huici and I. Moerman, *"Access Multi-Tenancy Through Small Cell Virtualization and Common RF Front-End Sharing,"* in Proc. of ACM WiNTECH, October 2017.

[6] C. Chang, N. Nikaein and T. Spyropoulos, *"Radio Access Network Resource Slicing for Flexible Service Execution,"* in Proc. of IEEE INFOCOM workshop on RS-FCN, April 2018

[7] X. Foukas, *et al. "FlexRAN: A flexible and programmable platform for software-defined radio access networks,"* in Proc. of ACM CoNEXT, 2016.

[8] X. Foukas, M. K. Marina, K. Kontovasilis, *"Orion: RAN Slicing for a Flexible and Cost-Effective Multi-Service Mobile Network Architecture,"*, MobiCom '17, October 2017.

[9] C. Hoymann *et al.*, *"LTE release 14 outlook,"* in IEEE Communications Magazine, vol. 54, no. 6, pp. 44-49, June 2016.

[10] 3GPP TR 23.711 V14.0.0, Technical Specification Group Services and System Aspects, *"Enhancements of Dedicated Core Networks selection mechanism"*, (Release 14), Sept. 2016.

[11] 3GPP TS 38.300 V15.0.0, *"NR; Overall description; Stage-2,"*, (Release 15), Jan. 2018.

[12] N. Nikaein, M. Marina, S. Manickam, A. Dawson, R. Knopp, C. Bonnet, *"OpenAirInterface: A Flexible Platform for 5G Research,"*, in Computer Communication Review, vol 44, pp. 33-38, 2014.

[13] I. Gomez-Miguelez, A. Garcia-Saavedra, P. D. Sutton, P. Serrano, C. Cano, D. J. Leith, *"srsLTE: An Open-Source Platform for LTE Evolution and Experimentation,"* ACM WiNTECH 2016, New York, USA, Oct. 2016.

[14] ETSI Plugtests Report, "*1st ETSI NFV Plugtests,*" Madrid, Spain, Mar. 2017.
[15] ETSI, *"Network Functions Virtualisation (NFV); Management and Orchestration,"* ETSI GS NFV-MAN 001, v1.1.1, Dec. 2014.

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