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Orchestration of RAN and Transport Networks for 5G: An SDN Approach

Ahmad Rostami, Peter Öhlén, Kun Wang, Zere Ghebretensaé, Björn Skubic, Mateus Santos, and Allan Vidal

The authors present an overview of the benefits and technical requirements of resource coordination across radio and transport networks in the context of 5G. Then they discuss how software defined networking principles can bring programmability to both the transport and radio domains, which in turn enables the design of a hierarchical, modular, and programmable control and orchestration plane across the domains.

Abstract

The fifth generation of mobile networks is planned to be commercially available in a few years. The scope of 5G goes beyond introducing new radio interfaces, and will include new services like low-latency industrial applications, as well as new deployment models such as cooperative cells and densification through small cells. An efficient realization of these new features greatly benefit from tight coordination among radio and transport network resources, something that is missing in current networks. In this article, we first present an overview of the benefits and technical requirements of resource coordination across radio and transport networks in the context of 5G. Then, we discuss how SDN principles can bring programmability to both the transport and radio domains, which in turn enables the design of a hierarchical, modular, and programmable control and orchestration plane across the domains. Finally, we introduce two use cases of SDN-based transport and RAN orchestration, and present an experimental implementation of them in a testbed in our lab, which confirms the feasibility and benefits of the proposed orchestration.

Introduction

Similar to previous generation mobile communications systems, advances in technology and society are influencing how the next generation mobile network, the fifth generation (5G), is shaping up [1, 2]. With 3G and 4G, mobile traffic shifted from traditional telephony services to data, and building on this success, 5G aims to provide unlimited access to information by people and a large variety of connected devices. We will see a massive growth in both traffic and the number of connected devices. New services will be developed and launched in shorter time cycles than current networks allow. End-user services will continue to develop, but there will also be an increasing volume of machine-type communications with very different requirements on the network, from networks of sensors and actuators to performance-critical industrial applications. To ensure that networks will be able to cope with the diverse landscape of future services, a variety of forums like the Next Generation Mobile Network Forum (NGMN), International Telecommunication Union Radiocommunication Standardization Sector (ITU-R), and 5G Public Private Partnership (5G-PPP) have defined aggressive performance targets for 5G systems to fulfill future requirements, including access bit rates up to 10 Gb/s and a significant reduction in latency [2]. It should be noted, however, that the most demanding requirements will not apply to all services, but the network needs to be flexible enough to accommodate different services in a cost-effective manner.

The digital and mobile transformations currently sweeping through industries worldwide are giving rise to innovative cross-sector applications that are demanding in terms of network resources. Programmability and operational scalability are key enablers for rapid innovation, short time to market for deployment of services, and speedy adaptation to the changing requirements that modern industry demands. Furthermore, as end-to-end services are increasingly deployed in a distributed cloud environment, this programmability should span all relevant domains, including the radio access network (RAN), various network domains, and distributed processing, in an orchestrated manner.

Software-defined networking (SDN) [3] is a promising approach to bring the required programmability to different parts of the network; in particular, a lot of research has been done in introducing SDN to fixed networks covering different network applications. Recently, there have also been efforts to adopt these ideas in wireless networks [4, 5], although this area is less mature in comparison to fixed networks. Nevertheless, very little has been achieved when it comes to coordinated resource control across all interconnected domains, something that — as we elaborate on below — is a key aspect of 5G networks, and is the main focus of this article.

In the following sections we detail the relevance of the programmability in the context of 5G, and explain the foreseen benefit of coordination among the different domains of transport, RAN, distributed processing environment, as well as network and service functions. We then present a scalable orchestration architecture, and two different network scenarios experimentally showing benefits of cross-domain optimization. These example scenarios are based on a centralized RAN (C-RAN) deployment model where the radio equipment's functionality is split between remote radio units (RRUs) and baseband processing units (BBUs), which are interconnected using the high-speed common public radio interface (CPRI) through a fronthaul network.

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Radio and Transport Interaction

Today, mobile networks are optimized for mobile broadband application. RAN and evolved packet core (EPC) functions are defined toward this backdrop even if additional applications are emerging, mostly in the Internet of Things (IoT) area (e.g., connected vehicles). Realization of these new use cases and services requires implementation of new features and capabilities in the network, which is a challenging and time-consuming task as it needs to go through lengthy standardization processes. This indicates that a more flexible and efficient way to add capabilities and customize deployments is needed, enabling network operators to support fast deployment of new services from a variety of applications and industries. It is already possible to share a network infrastructure among several mobile virtual network operators (MVNOs), each with its own business processes and customers. However, the MVNOs do not have the possibility to adapt to new features and capabilities in the network as required for new services.

In 5G, the concept of network slices is introduced, where each slice can span several segments of a network and be customized to support a specific service. Such services range from evolved mobile broadband and media distribution to different IoT applications, and even include applications and services that have yet to be defined. One important enabler for this is the decomposition of the mobile core functionality into granular functions and virtualization of them following the concept of network functions virtualization (NFV) [6, 7]. This enables flexible placement of the different virtualized network functions (VNFs) in centralized or distributed execution environments. For example, in a media distribution slice, core functions and caches could be placed close to a distribution location to optimize the performance. Efficient realization of this, however, requires coordination with the transport network, which provides connectivity among the VNFs.

Industrial remote control applications constitute another set of use cases, which have high requirements on the network in terms of availability, latency, and bandwidth. To fulfill end-to-end service requirements of these applications in a dedicated slice, each component of the slice needs to meet specific requirements. This includes processing performance, function placement, radio characteristics, and transport network.

Looking specifically into 5G radio, new challenges arise from a transport network perspective [8, 9]. In fact, already concepts are in development where the different domains of radio and transport can exchange performance data and optimize user experience by cross-domain optimization of traffic flows [10]. From the 5G deployment perspective, densification of the radio network by small cells implies that a user equipment (UE) will often be in the range of several radio base stations. Selecting a base station involves not only radio parameters, but also transport network performance. If a backhaul link experiences high packet loss, we would like to push services with higher requirements to different base stations with better transport connectivity. This type of load balancing requires information from both RAN and transport, and a UE may also be connected across different access technologies, which increases the need to coordinate between different technology domains.

In dense radio deployments, interference levels increase, which at times requires radio coordination capabilities for mitigation. However, the method used for handling interference depends on the deployment model. In a centralized baseband deployment, tight coordination features such as joint processing can be implemented at the cost of typically high CPRI bandwidths and stringent delay and jitter requirements. In traditional Ethernet or IP-based backhaul, tight coordination requires low-latency lateral connections between participating base stations.

In a traditional C-RAN architecture, the fronthaul connectivity is static. Introducing a flexible fronthaul network enables dynamic allocation of BBUs and RRUs, and a number of optimizations can then be applied [11], e.g.

- *Energy saving*: BBUs and RRUs can be put in a low-power state in times of low traffic.
- *Dynamic clustering*: To enable joint baseband processing, RRUs can be dynamically clustered into groups to optimize coordination gains.
- *Pooling*: Some scenarios allow for a reduced number of BBUs by flexibly allocating processing capacity to radio cells where demand is higher.
- *Shared fronthaul*: A fronthaul operator can share the network among several radio network operators to optimize use of the fiber infrastructure.
- *Resilience*: In cases of failure in BBU pools and/or transport connectivity, a coordinated mechanism is needed to restore the network to normal operation, or, if this is not possible, to at least ensure that basic coverage and operation are secured.

While the flexibility gain of such approaches has to be evaluated against the increased complexity, these different examples point to the value of increased flexibility and programmability, and more coordination among different parts of the network. Bringing the different domains together is a challenge from both the technical and operational perspectives. Later we adopt an SDN-based orchestration architecture spanning the different technology domains of transport, radio, and cloud to solve these issues. But before that, in the next section we present an overview of other requirements for developing a cross-domain orchestration architecture and enabling technologies.

The Need for Programmability

Meeting the objective of flexibility requires as a first step that the actual resources in the infrastructure can be adapted and changed dynamically without manual intervention by an operator. In addition, we need methods and procedures to develop applications and services on top of a flexible infrastructure, across different technology domains. To fulfill these requirements, a control architecture with a high level of *programmability* is required. Specifically, the control architecture should not be bound to a particular use case or scenario, and should enable a network operator to program customized algorithms into the control plane for optimization of RAN, transport, and cloud resources.

In addition to this overarching objective, the following features are required:

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In a RAN, separation of data plane and control plane logic has been an important concept for a long time in the different technology generations. A somewhat more recent development is the self-organizing network framework, which uses a centralized SON controller to optimize network parameters and configurations on a coarse timescale.

Modularity: The control architecture should follow a modular architecture with well-defined control functions and interfaces. The interfaces and architectural building blocks should also support stacking in a recursive manner, to enable system deployments adjusted to specific scenarios.

Virtualization: The architecture should have the capability to divide physical and virtual resources of the infrastructure into separate groups (or slices) and allocate these to different clients. Here, clients can be higher-level controllers or service functions and applications. Dedicated slices should be isolated from each other for both security and performance reasons (e.g., to prevent an overloaded slice to negatively affect other slices).

Scalability: Control of resources in each of the domains is a complex task, as it usually requires dealing with a large number of network elements as well as that of control parameters and procedures. Therefore, joint control over the domains could easily become intractable, which should be avoided by proper design of the control architecture. Suitable abstraction methods are also needed to limit the complexity in higher layers and make the global optimization problems manageable.

To meet these requirements, we adopt SDN principles in the design of the overall control and orchestration architecture.

SDN

Programmability has been a hot topic in networking research for the last 25 years. Over the years several approaches, ranging from active networks to multiprotocol label switching (MPLS), have been explored for bringing more flexibility into the networks. SDN is the latest attempt in the quest for network programmability, and it has attracted much attention in both academia and industry. The SDN concept can bring the needed programmability in the transport part of mobile networks.

Through SDN, the main intelligence of the network control is decoupled from the data plane elements and placed into a logically centralized remote controller. This allows a network operator to directly program customized control algorithms into the network. A key concept of SDN is the abstraction of network elements (e.g., switches, routers, and access points) and specifying corresponding application programming interfaces (APIs) [3]. OpenFlow is an example of SDN abstractions, where switches' forwarding functionality is abstracted in the form of one or more flow tables, and the OpenFlow protocol specifies methods for programming the behavior of the tables by a remote controller [12].

SDN also enables creating multiple layers of abstractions on top of the controller in a recursive way. For example, a layer of abstraction on top of the SDN controller of a large network can hide all the details of that network and present the whole network as a big switch. This improves the modularity and scalability of the control architecture.

Programmable RAN

In a RAN, separation of data plane and control plane logic has been an important concept for a long time in the different technology generations. A somewhat more recent development is the self-organizing network (SON) framework, which uses a centralized SON controller to optimize network parameters and configurations on a coarse timescale (e.g., adjustment of power between neighboring radio base stations).

There is, however, a need for enhanced programmability in the RAN. One driver for this is the need for flexibility in supporting all different services in a timely manner. In research, there has been interest in SDN-like approaches in radio networks [4, 5]. In [4] a concept for software-defined fronthaul is presented along with some relevant use cases. It is also noted in [5] that mobile networks deal with a fundamentally different problem in complex radio environments, whereas SDN in packet networks mostly addresses forwarding. Consequently, solutions will be different, and [5] presents requirements for software-defined mobile networks.

In the transition to 5G, there are ongoing discussions on how to split the radio functionality. The current BBU/RRU and the associated CPRI may not be the best option going forward. Still, functions closer to the air interface with strict real-time characteristics should continue to be deployed on specialized hardware. But other functions could be deployed on general-purpose hardware, possibly in a virtualized environment [13]. Add to this the possible placement of mobile core and service-specific functions on distributed execution environments, possibly co-located with radio functions. Then the need for coordination between dedicated radio hardware, network functions, processing environment, and transport connectivity becomes more obvious.

Cross-Domain Orchestration Architecture

In this section, we present a hierarchical cross-domain orchestration architecture, which follows the SDN principles and addresses the above-mentioned challenges for programmability and flexibility. The proposed architecture is depicted in Fig. 1. At the bottom level of the architecture we have heterogeneous sets of resources distributed across different domains. These include radio, transport, as well as cloud (compute and storage) resources. The radio resources are primarily at the access edge of the network. The transport resources are distributed across different parts of the network (e.g., access and aggregation) and usually encompass different technology domains like packet, optical, and microwave networks. The cloud resources are also distributed across the access/aggregation and core of the network for hosting various VNFs.

Resources within individual domains are controlled through a domain-specific controller in a programmable way. A domain controller — through a programmatic northbound API — exposes the domain capabilities to higher-layer controllers/orchestrators, and enables them to dynamically program the corresponding resources. Typically, a controller exposes an abstract view of the domain resources over the API, and hides most of the details. Designing the abstraction layer on top of a domain typically involves a trade-off between the optimal resource utilization and the simplicity and scalability of the operation and control. Specifically, exposing more detailed information of domain resources enables higher layers to make optimized resource allocations, but on the other hand increases the complexity of higher-layer controllers/orchestrators as they will need to deal with lots of information and updates

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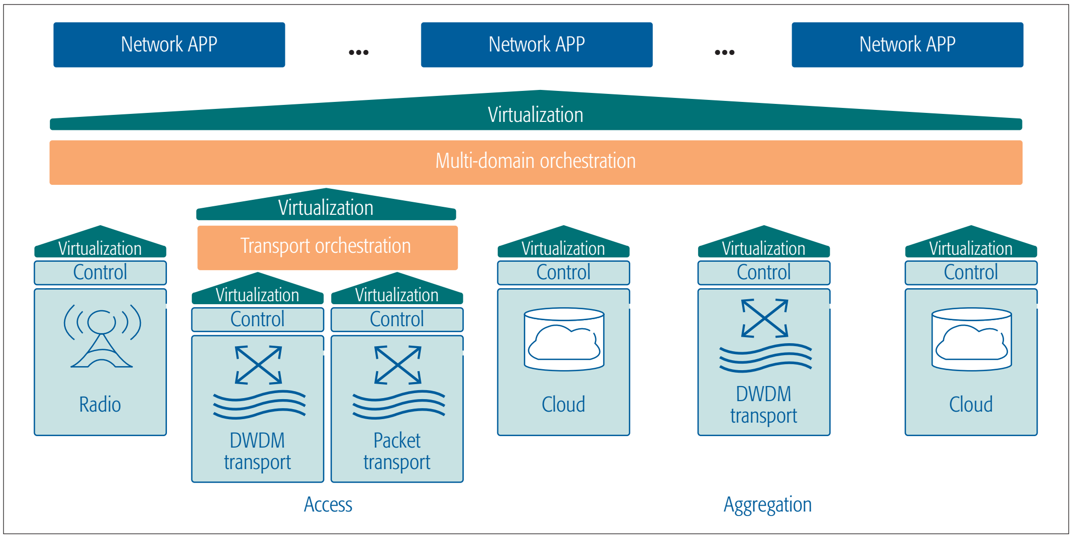

Figure 1. Hierarchical cross-domain orchestration architecture.

The mapping of service requests to the resources should on one hand fulfill the performance requirements of the services, e.g. in terms of bandwidth, latency and compute resources, and on the other hand target the optimization of the resource utilization across the network.

[14]. Additionally, a controller can take its client's needs as input for deciding the level of abstraction. Obviously, the level of abstraction requested by a client should be within the policy defined by the operator. Furthermore, the controller might virtualize the resources and allocate slices with different levels of abstractions to higher-layer clients.

To elaborate on the domain-specific controller, let us make an example. Consider a wavelength-switched optical transport network, where a centralized SDN controller manages the network resources as described in [11]. The SDN controller has comprehensive knowledge of the network topology and optical resources (e.g., available wavelengths and transceivers), and implements a routing and wavelength assignment algorithm. On its southbound interface the controller communicates with the optical devices to configure the wavelength switching tables. And on its northbound API the controller hides all optical details and presents the whole domain as a single optical cross-connect (OXC) whose ports are the ingress/egress ports of the optical domain.

On top of the domain controllers, there are one or more layers of orchestration — usually separated into service and resource orchestration layers. The service orchestrator takes high-level definitions of services and applications, and translates these into lower-level components using a catalog with pre-defined building blocks. It also handles life cycle management with tasks like service deployment and upgrades. It interfaces to one or several resource orchestrators, where the actual resources are handled for realizing the service. The resource orchestration layer combines resources of the same or heterogeneous types across multiple domains into a unified resource representation. For example, a transport orchestration layer in the access segment of the network combines abstract views of resources from multiple transport domains (e.g., packet and optical networks) to create a unified and technology-agnostic presentation of transport resources in that segment (Fig. 1). Similarly, at the topmost layer of the resource orchestration radio, the transport and cloud domains are combined to create a unified abstraction of resources. The unified abstraction is then exposed directly toward network applications or the service orchestration over a programmatic API. In the following, we focus only on the resource orchestration functions and how network applications can dynamically program the resources, as needed, through this API.

Also note that as we move up the control/orchestration layers, the resource presentations become more abstract. Therefore, a key function of an orchestration layer is mapping the requests coming from a network application or a higher-layer orchestrator to lower-layer orchestration and control. In other words, requests arriving at the topmost layer of orchestration are expressed at a very abstract level, and they are translated into more concrete configuration requests as they are passed down the control plane layers, until the lowest-layer controllers translate them to domain-specific configuration commands. The mapping of service requests to the resources should on one hand fulfill the performance requirements of the services (e.g., in terms of bandwidth, latency, and compute resources), and on the other hand target the optimization of the resource utilization across the network.

Additionally, a virtualization layer on top of a resource orchestrator enables the unified set of resources to be sliced and allocated to different network applications. As discussed before, this enables efficient sharing of an operator's resources among several network applications or service providers.

A key aspect of the orchestration architecture is to specify the abstractions and interfaces between different control and orchestration layers. While there are many approaches for abstracting resources of individual domains, designing combined abstraction models for heterogeneous resources is a challenge, and is a subject of ongoing research. For example, the European project UNIFY has proposed a joint abstraction of networking and compute resources in the form of a big-switch big-software (BiS-BiS), which presents a virtualization of a networking element connected with a compute node [15]. In this model, the resource requests between the resource orchestration layers can be recursively expressed as network function forwarding graphs (NF-FGs), where an NF-FG presents a mapping of a group of NFs

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The programmability feature is realized through the orchestration's northbound API, which allows network applications to implement customized optimizations across radio, transport and cloud domains. As for the modularity, adding a new technology domain to the control plane is straightforward, and does not require changes to the existing parts.

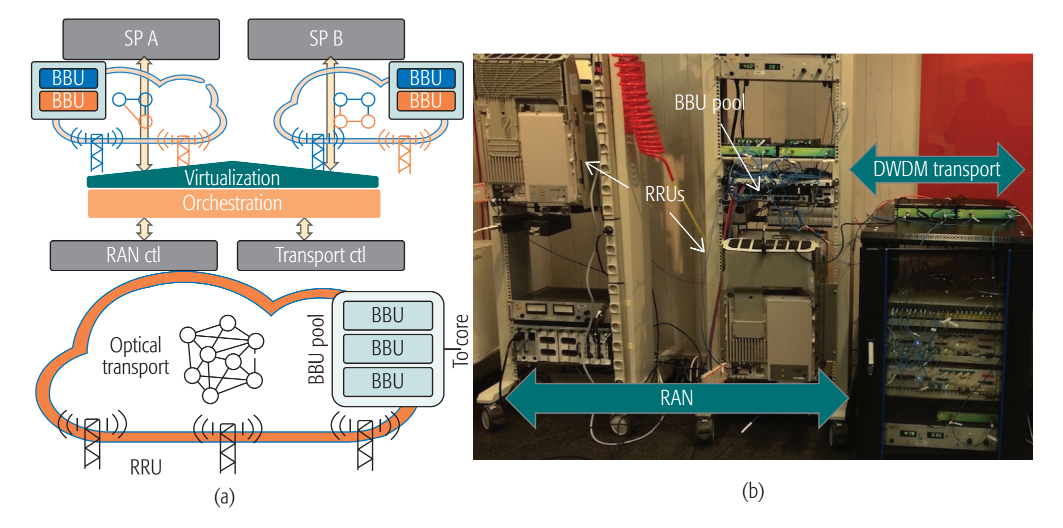

Figure 2. a) Architecture of the RAN-transport orchestration testbed; b) a snapshot of the experimental testbed showing RAN and optical transport domains.

and their corresponding forwarding overlay into the abstract view of the infrastructure (i.e., BiS-BiS) [15]. In the next section, we explain how we adopt this concept for creating joint abstractions of radio and transport resources.

Let us now elaborate on how the presented control architecture meets the requirements mentioned in the previous section. The programmability feature is realized through the orchestration's northbound API, which allows network applications to implement customized optimizations across the radio, transport, and cloud domains. As for modularity, adding a new technology domain to the control plane is straightforward and does not require changes to the existing parts. Also, a service provider can perform the cross-domain orchestration and optimization of resources on top of any combination of owned and leased domains, thanks to the virtualization on top of every control/orchestration layer. Finally, scalability is supported through several layers of abstractions, where specific details of each domain are hidden below corresponding abstractions.

Use Cases and Proof of Concept

In this section we present two use cases of the cross-domain orchestration, which we have experimentally demonstrated in a testbed in our lab. The objective is to demonstrate the feasibility as well as benefits of the designed architecture. The use cases particularly focus on the RAN-transport orchestration to fulfill the requirements of 5G. However, for the sake of simplicity, in our testbed we utilize existing 4G radio access points and a mobile core network. The first use case presents sharing of joint RAN-transport resources between two service providers (SPs), and the second one demonstrates how an SP can customize its own slice.

Radio-Transport Orchestration Testbed

Our testbed is composed of the following two domains:

- Mobile broadband domain: provides broadband services to mobile users employing LTE technology. The domain is composed of a group of LTE access points, deployed according to the C-RAN architecture. The mobile network relies on wavelength connectivity services of the transport domain for CPRI transport.
- Optical transport domain: is a dynamic wavelength routed network based on dense wavelength-division multiplexing (DWDM) and provides programmable fronthaul services to the mobile network at the wavelength level. The domain is composed of optical DWDM switches, optical add/drop multiplexers, and tunable transceivers.

Figure 2 depicts the architecture of the testbed together with a snapshot of the physical equipment deployed for this purpose. The control/orchestration plane of the testbed is realized following the architecture presented earlier.

The transport domain is controlled by the open source SDN controller OpenDaylight [16]. The controller has been customized to support circuit-switched network control and optical path computation, and a southbound plugin has been developed to allow configuration of the optical switches over their existing command line interfaces (CLIs). Also, an abstraction layer on top of the controller is implemented, which adopts the BiS-BiS model and presents the transport domain as a large OXC over an NF-FG interface toward the orchestrator (Fig. 3). For the mobile domain we use an existing CLI-based RAN manager that centrally controls the RAN resources. The RAN control functions include activation and configuration of cells, assignment of BBU resources to RRUs, as well as management of users' handovers among cells. We model the functionality of RRUs and each baseband processor (i.e., BBU) as individual NFs, which enables us to abstract the RAN resources as a BiS-BiS model. Then the orchestrator combines the BiS-BiS models of the RAN and transport domains into a unified model. The orchestrator with the NF-FG interfaces has been realized in Python.

Scenarios and Results

The first use case demonstrates sharing of a mobile access network infrastructure between two service providers. For realizing the infra-

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structure sharing, the orchestrator's virtualization layer implements joint slicing of resources in the RAN and transport domains. The radio resources included in the slicing are RRUs and BBUs. Figure 2a illustrates an example of the overall view of the resources at the infrastructure provider level, and the virtualized view presented to any of the two SPs (the smaller clouds in the figure). There are two types of virtualized resources: dedicated (shown in blue in Fig. 2a) and shared (orange). While dedicated resources are guaranteed to be at the disposal of an SP at all service operation times, the shared resources can be used by either of the SPs at any time. The orchestrator ensures the isolation between the dedicated resources of each SP and also resolves possible conflicts for using the shared resources according to a sharing policy. The slicing of the resources with a first-come first-served sharing policy is successfully realized in our testbed.

In the second use case, we demonstrate how SP A can run a customized optimization of radio and transport resources within its allocated slice. The infrastructure provider's orchestration is configured to provide a group of dedicated transport and radio resources to SP A as illustrated in Fig. 3. These include:

- Four RRUs distributed across a residential and a business area. Each area is equipped with two RRUs: a macrocell and a small cell. While the macrocell provides the coverage across an area, the small cell is used for providing additional capacity in the area if needed
- A pool of three BBUs
- Three optical connections abstracted as a 3:4 OXC, which can be dynamically reconfigured to connect any of the three BBUs to any of the idle RRUs

SP A utilizes the allocated resources to create an elastic mobile broadband (EMBB) service, where the service capacity is dynamically and automatically scaled up and down — when and where needed. The trigger for scaling the service capacity comes from live monitoring of the service demand in the RAN. The monitoring is performed through measuring the throughput of active cells by the RAN controller, upon request from the SP. The EMBB service logic has three states (Fig. 4a). In state 1 (the default state), only the two macrocells are activated, providing coverage in both areas. When extra demand is identified by the EMBB service manager (residing inside SP A), the corresponding small cell is activated (state 2 or 3). To do that, the service manager requests the orchestrator to reprogram the testbed to adjust the service capacity through de/activating small cells. The orchestrator translates the request into required configurations in the transport and RAN, and the configurations are applied in the data plane by the corresponding controllers. For example, activation of a new RRU involves assigning and configuring appropriate BBU resources from the BBU pool, and establishing the wavelength connectivity between the RRU and the assigned BBU. Note that only one small cell is activated at a time to serve the area with a higher demand. This demonstrates dynamic reuse of resources where a four-cell RAN requires only three optical connections and three BBU resources. In a real deployment, there would be many more RRUs and BBUs. Our numerical analysis, although not presented here, indicates that implementing the EMBB service in a metro area with hundreds of RRUs leads to a saving of around 30 percent in terms of required transport and radio resources [17].

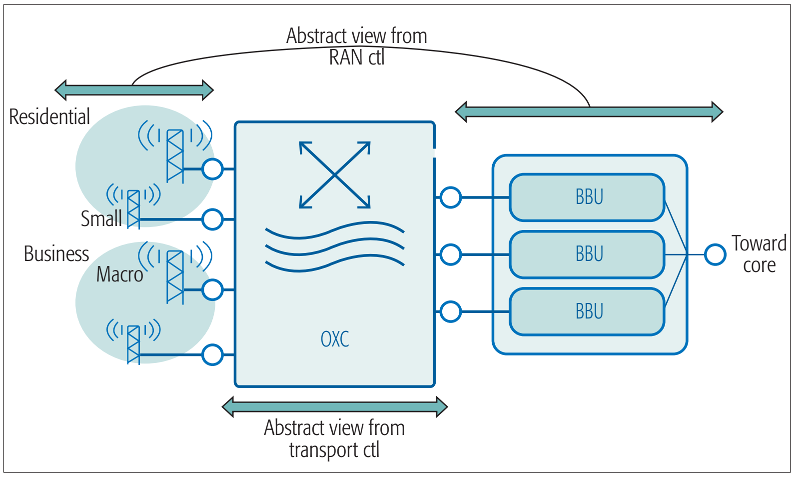

Figure 3. Abstract view of resources exposed by the infrastructure provider's orchestrator toward SP A. The orchestrator creates the abstract view by combining views received from transport and RAN controllers.

Figure 4b shows a representative example of traffic measurements performed during the runtime of the EMBB service in our testbed. The presented traffic measurements clearly show the transition among states 1, 2, and 3 over the runtime of the system.

The use cases above demonstrate the value of a global cross-domain orchestration for both an infrastructure provider and its customers (i.e., SPs). The infrastructure can share its resources among different customers, leading to better resource utilization and higher revenues. At the same time, the customers can run their own customized control mechanisms, leading to a much shorter time to scale services or to create new ones.

Conclusion

Fast introduction of new services and dynamic scaling of them are among major expectations on future networks in general and 5G in particular. Flexibility in all networking domains is a crucial requirement to fulfill these expectations. Furthermore, coordinated control of heterogeneous resources across multiple domains is needed, and SDN is a promising approach for bringing the flexibility and realizing the required coordination. In view of this, we present an SDN-based cross-domain orchestration architecture and validate it by experimental realization of two use cases. The use cases, which are based on joint slicing of RAN-transport resources and the EMBB service, demonstrate the benefits of the joint orchestration for both infrastructure providers and service providers. Specifically, service agility and efficient resource utilization are among the main benefits of the proposed orchestration architecture.

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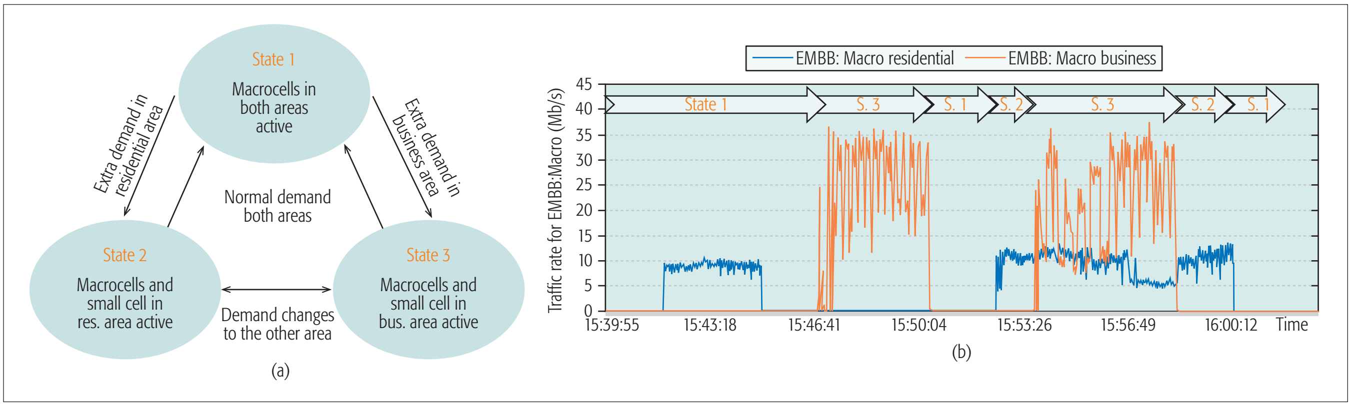

Figure 4. a) State diagram of the EMBB service; b) traffic measurements of the service: the demand threshold to activate a small cell is set to 10 Mb/s. The arrows indicate states (transition) during the service operation. UEs connected to the macro RRUs are configured to download large videos to trigger state transition.

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