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Radio Resource Sharing as a Service in 5G: A Software-defined Networking Approach

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Abstract—The rise of heterogeneity in technology, types of services, and coverage area of radio access in the Fifth Generation (5G) wireless communication, opens new challenges in optimising users' access to the networks. To fully utilise the capacity of such rich field of wireless connectivity, mobile devices can not any more be confined with accessing only their previously agreed home operator's infrastructure. On the other hand, and in order to keep up with the agility required to deliver promises in providing new services and applications, virtualization and softwarization are introduced in the 5G. To this end, we propose an on-the-fly Radio Resource Sharing (RRS) scheme between different mobile infrastructures so as to provide mobile devices with the freedom to access all available radio resources around them. Such on-the-fly RRS is empowered by employing the concepts of Software-defined Networking (SDN) and virtualization of radio access resources. We argue that the RRS service is a step forwards in achieving the convergence as foreseen by the 5G: convergence of SDN, virtualization, and wireless control, convergence of heterogeneous wireless infrastructure, and above all, convergence of different operators' infrastructure in a transparent manner.

Index Terms—5G mobile; radio resource sharing; Software-defined networking; virtualization; device-centric networking;

I. INTRODUCTION

While the requirements and details of technologies for the Fifth Generation (5G) wireless communication are not yet defined, it is foreseen that 5G will be a result of convergence, of services, platforms, and standards. Such multi-radio converged network calls for an efficient utilization of the overall available resources to carry user traffic while providing an advanced users' quality of experience (QoE). A question of fundamental importance to the operators and vendors is how to assign and distribute the given traffic within the available wireless radio access network (RAN). The significance of this question is twofold. Controlling of traffic load on various radio access, to ensure well-utilization of all infrastructure on one hand, and delivering the new promised quality (i.e. throughput and latency) as well as meeting users' expectation on the other hand should be addressed.

The concept of virtualization of resources has been studied in mobile networks so as to reuse the infrastructure in a dynamic and flexible fashion. In particular, RAN virtualization and Cloud RAN is well discussed both in research and in industry over the past few years [1]. Since virtualization enables more software-based control in the network, the concept of Software Defined Networking (SDN) in the control plane of mobile networks has been exploited in the literature [2], [3], [4]. SDN allows for easier and more cost efficient evolution in

the data plane without depending on a slew of management or control protocols, provides centralized control of the overall infrastructure, and delivers a richer feature set based on its programmable nature. One of the advantages of the virtual RANs and the SDN-based mobile network control is the flexibility of accessing different RANs, potentially belong to different operators, depending on the traffic load instead of the traditional access to only home operators.

To this end, and by using the concept of virtual RAN, we present an on-the-fly Radio Resource Sharing (RRS) scheme between different mobile infrastructures so as to provide mobile devices with the freedom to access all available radio resources. In order to support such degree of freedom, we present an SDN-based network architecture that enables instantiations of virtual entities at the radio access network. We propose two different SDN enforcement approaches depending on the trigger and control of the RRS. In the first approach, referred to as the device-centric approach, we consider that trigger and selection of the on-the-fly instantiation of virtual attachment points are performed at the user terminals based on (1) their current measurements of the radio and (2) auxiliary information provided by the network. In the second approach, referred to as the network-centric approach, we consider that the SDN enforcement decisions, i.e. trigger and control, are performed at the network based on (1) radio signal measurements provided by the user terminals, and (2) network status updates provided by the network infrastructure elements. We study the performance enhancements in terms of expected figures of merit, and also demonstrate that more dynamic and efficient utilization of resources is accomplished. We further argue that the RRS as a service can pave the path for new revenue models. For example, constructing the global view by means of a logically centralized SDN control, based on the radio and network measurement collected by the network, enables operators to effectively predict the spatiotemporal availability of radio-resources throughout the infrastructure, and allow them to implement real-time spectrum auction schemes.

The remainder of this paper is organised as follows. In Section II we summarize the related works. In Section III, the architecture of mobile networks based on which we propose the RRS service is depicted and details of its elements are explained. The research challenges for accomplishing our proposed RRS service and the associated architecture are discussed in Section IV. In Sections V and VI, the device-centric

and network-centric approaches are thoroughly explained. Section VII elaborates the setting in which we examine the performance of RRS service. We analyse results of the two different approaches here. Finally, overview of the highlights are detailed in Section VIII.

II. RELATED WORKS

Mobile network operators need to face the even increasing demand of data traffic in a cost effective manner. As the spectrum is a scarce resource, mobile operators are stressed to devise solutions for leveraging additional capacity across multiple radio access technologies (Multi-RATs). To this end, there is a big interest in the research community in designing architectures that aggregate different radio technologies and offer a multi-radio converged network to the end user in a transparent manner. The cellular standardization community, a.k.a. Third Generation Partnership Project (3GPP), has made a big effort in developing specifications that address inter-working among cellular and Wireless LAN (WLAN) technologies, e.g. solutions for enabling trusted access to 3GPP services with WLAN devices and for supporting the access network discovery and selection function (ANDSF) [5]. Moreover efficient network selection algorithms are needed to enable users to connect to the best RAT in an efficient manner. The network selection algorithms for Multi-RAT can be classified in two groups [6]: 1) user-centric approaches where the users are continuously monitoring the link quality with all the neighboring base stations and steer traffic to the access point with the best quality and 2) RAN assisted approach: where the users combine their signaling measurements with additional knowledge of the loading information from the network infrastructure. Although the latter approach ensures better performance, it is more complex.

The aim of our paper is to apply an SDN approach for enabling a less complex network selection process [7]. We believe that the proposed RRS service can improve the radio resource management (RRM) operation in a Multi-RAT scenario due the larger knowledge of the network state that can be achieved by employing the SDN technology. One the most candidate technology for enabling Multi-RAT 5G architectures is the C-RAN technology proposed in [1]. Even though the benefits of C-RAN are clear its integration into the existing cellular architecture requires a smooth transition between prominent 3GPP systems (e.g. LTE-A) and forward-thinking 5G architectures. Some hybrid approaches are needed to enable a soft transition from the current mobile architectures to the future 5G system. SDN and Network Virtualization (NV) are envisaged as the key enabler technologies for that purpose, as they can be used to improve scalability and enable service oriented-management in the current architectures in a less invasive manner. To this end, a plethora of works have risen in the literature to exploit the potential benefits of SDN/NV in future 5G networks. In [8] the authors discuss the key benefits and the key challenges of applying SDN in wireless and mobile networks, describing the main features of the SDN-based mobile architectures. The authors in [9]

propose an SDN architecture specific for the Long-Term Evolution (LTE) system, which enables infrastructure sharing among different RAN technologies. Network sharing in the context of 5G and network slicing has also been discussed in [10]. Even though this work is clearly a first attempt towards an SDN-enabled RAN, several open issues are yet to be solved, e.g. how to deploy the proposed solution in the current mobile network architecture in a non-invasive manner.

Other research works are focusing on the design of SDN-Controller architectures for wireless networks with the aim to enable flexible sharing of network resources among multiple operators, referred to as tenants. In [11] authors propose a two-tier dynamic SDN-Controller architecture for wireless backhaul networks that aims at balancing the tradeoff between scalability and system performances in shared wireless networks. In [12] authors propose an SDN controller architecture for controlling multi-tenant slices in a shared RAN. Different from [11] [12], in this paper we focus more on evaluating the impact of the proposed RRS service in the current mobile architectures. Moreover in this paper we provide our vision on how to enable dynamic sharing of the network resources among multiple operators in a Multi-RAT scenario in a less invasive manner. Furthermore, how an abstraction of mobile network topology can be shaped within the SDN-Controller and allow for selection of RAN during handover, is presented in [13].

It is worth to note that dynamic and flexible network sharing is a key requirement of future 5G networks as it can enable operators to face the increasing demand for traffic in a cost effective manner, by maximizing the resource utilization efficiency. 3GPP has recently outlined a suite of requirements and guidelines for network sharing [14], specifying the architecture and procedure to enable different operators to share the RAN and proposed two different approaches for RAN sharing, named Multi Operator Core Network (MOCN) and Gateway Core Network (GWCN) respectively. In the MOCN approach the RAN is shared among multiple operators, while each operator owns an independent core network. In the GWCN approach, in addition to RAN, the operators share the Mobility Management Entity (MME). Note that the MOCN is considered more flexible than the GWCN approach as it can be used to enable inter-networking with legacy networks and mobility among multiple radio access technologies.

The concept of RAN sharing has been analyzed in our previous work [15] where we propose a framework that permits the flexible sharing of virtualized LTE evolved Node Base station (eNB) among multiple operators. In this framework the virtualization of the eNBs is dynamically handled in an SDN fashion, enabling one operator to offload traffic on-demand to the base stations owned by other operators. In another work [16] we propose an SDN-based framework for enabling elastic spectrum sharing in multi-operator environment of Frequency Division Duplex (FDD) macro eNBs and Time Division Duplex (TDD) pico-eNBs. The aim of this framework is to enhance flexibility and the resource management efficiency by enabling an SDN-based coordination of network resource
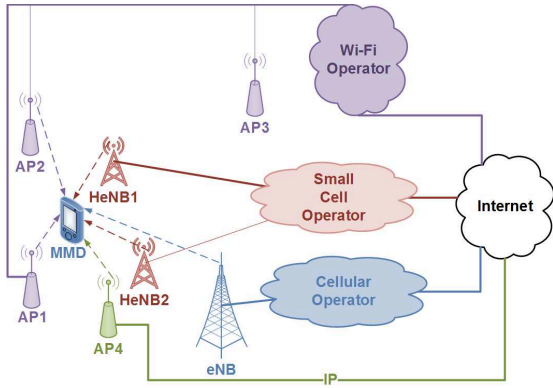
Fig. 1. Motivating Example and Main Idea.

management process. Different from [15][16], in this paper we focus more on the resource sharing aspects in multi-domain environment consisting of cellular base stations, femtocells and WiFi access points (APs).

In short, the contribution of this paper to the state of the art can be summarized as follow:

- We present a SDN-based architecture that enables the RSS service in a less invasive manner, e.g. as compared to the C-RAN approach.
- We present the logical signaling flow of the proposed service and discuss the implication of adopting the proposed service in a real-life network.
- We provide a performance evaluation of the proposed service, considering a multi-domain scenario.

III. REFERENCE ARCHITECTURE

In this section, we present the reference architecture for RRS as a service in the 5G network. First, we summarize the rationale behind the proposed SDN-based architecture for RRS as a service in 5G, and then we outline key features of the proposed SDN-based architecture.

A. Motivation and Main Idea

Over the past few years, wireless networks have transformed from a set of single-tier operator-deployed circuit-switched systems, designed to support voice-centric services in wide geographical regions, to a set of multi-tier networking clusters of IP-based RATs, designed to support heterogeneous communication capabilities and diverse networking requirements. The nowadays heterogeneous wireless network is composed by tower-mounted cellular Base Stations (BSs) providing wide area coverage (a.k.a. macrocells), user-deployed low-power and small-sized BSs for boosting the area spectral efficiency of the licensed spectrum (e.g. femtocells), wireless local area network APs for enabling high-data rate connections to the Internet over the unlicensed spectrum, as well as other low-power low-cost sensors (e.g. energy monitoring in the smart grid). In such a heterogeneous layout, the mobile users can typically access only a closed set of network infrastructure elements that are either open for public access, e.g. hotspots

in a public building, or owned by a mobile network operator with which they maintain a long-term contract, e.g. the cellular BSs owned by the home cellular operator. Nonetheless, when a mobile device is located outside the geographical coverage area of the home operators' network, existing roaming architectures ensure that it will maintain the ability to automatically access all services of the home operator. In such occasions, the mobile device is typically served by a visited network with which the home network has established a-priori Service Layer Agreements (SLAs).

The employment of the aforementioned two business models, that is (1) access only to the infrastructure owned by the home operator and (2) network roaming, ensures that the home operator will provide appropriate service charging and customer support services to the end user. It is worth to note that in a typical roaming scenario the home operator doesn't have control of any resource of the host operator but it can just request a roaming service to the host operator for the end users registered to the home operator. The host operator, in turn, controls and manages its owned resource to provide the requested service to the end users of the home operator.

Besides, **network coverage** and **user throughput** have been the cornerstone of competition between the mobile network operators over the past few decades and the key criteria for designing mobile operators' networks. Nonetheless, since cost-effectiveness, energy-efficiency, and delivered quality to the users, attract a surge of interest over the past few years [17], current design practices should be re-assessed in the context of the fifth generation network, a.k.a. 5G network.

In this direction, our work aims at surpassing the performance limitations inherent to the direct relation between ownership of infrastructure and offering mobile services. Hence, we are discussing an architecture in which mobile users are allowed to access IP-based services through all available network infrastructure by introducing more effective and highly robust RRS among different network operators. To this end, we exploit the flexibility offered by the SDN technology in order to allow **on-the-fly RRS** among mobile network operators in a transparent fashion for the mobile device. The main idea of the proposed SDN-based solution is to support the **dynamic instantiation of virtual attachment points** that can be readily accessed by the end users independent of the users' home network infrastructure. We use some key features of the SDN technology that can emulate operation of a typical attachment point owned by the home operator of the end user for non-home users.

We further investigate the performance of the proposed SDN-based architecture under two different SDN enforcement approaches depending on the **trigger** and **control** of the proposed SDN-based solution. In the first approach, referred to as the **device-centric approach**, we consider that the trigger and the selection of the on-the-fly instantiation of virtual attachment points are performed at the user terminals based on (1) their current measurements of the radio and (2) auxiliary information provided by the network side. In the second approach, referred to as the **network-centric approach**, we

iMMD	(H)OpeNB	OpeNAP	SDN-Controller	SDN-Server
✓Able to connect to other than home operator	✓Enables access to non-registered users	✓Enables access to non-registered users	✓Orchestrates the RRS service in the domain of a single network operator	✓Orchestrates RRS service among multiple operators
✓Implements open interface functionality	✓Implements a Hypervisor Layer in between the PHY and the L2 layers	✓Implements a Hypervisor Layer in between the PHY and the MAC layers	✓Remotely adapts the RRS strategies at the Hypervisor Layer of the (H)OpeNBs/ OpeNAPs	✓Is the reference point for initiating the RRS service
✓Measures radio signals, and estimate its location	✓Hosts multiple VeNB instances (up to one per LTE-A operator)	✓Hosts multiple VAP instances (up to one per Wi-Fi operator)	✓Remotely create & manages the VeNB/VAP instances at the (H)OpeNBs/ OpeNAPs	✓Triggers the SDN-Controller to create & manage a VeNB/VAP instance
✓Collects status of network from SDN-Controller	✓Collects MMDs' measurements and assesses its own status	✓Collects measurements from the MMDs and assesses its own status	✓Monitors the MMD/ (H)OpeNB/ OpeNAP status in the network operator's domain	✓Monitors spatiotemporal availability of resources among different domains
✓Collects analytics of network from SDN-Server	✓Supports logical interfaces between the instantiated VeNBs and home operators	✓Hosts the SDN-Controller in the case of standalone APs	✓Establishes, monitors and controls existing tunnels to other network domains	✓Reference point for establishing direct communication tunnels among network domains
✓Runs an intelligent agent to trigger measurements and updates	✓Provides local SDN-Controller with medium-term predictions of resource availability	✓Provides local SDN-Controller with medium-term predictions of resource availability	✓Monitors and hosts the SLAs -Participates in spectrum auction based on resource availability	✓Monitors and hosts the SLAs -Regulates the spectrum auction phase

consider that the SDN enforcement decisions, i.e. trigger and control, are performed at the network side based on (1) radio signal measurements provided by the user terminals and (2) network status updates provided by the network elements.

Aiming to better highlight the rationale behind the proposed SDN-based solution, in Fig. 1 we provide an illustrative example to show the potential benefits of the on-the-fly RRS, e.g. traffic offloading, coverage improvements, etc. Without loss of generality, in Fig. 1 we consider a network scenario composed of a macro-cellular LTE-A network operator, a small cell LTE-A network operator, a Wi-Fi network operator, and a stand-alone (private) WiFi AP. In this scenario, we assume that the device, named as Multi-Mode Device (MMD), is equipped with both Wi-Fi and cellular radio access interfaces and has long-term contract with the macro-cellular LTE-A network operator – in Fig. 1, the tagged MMD is associated with the eNB. Under certain conditions, the home operator may desire to offload the traffic of the MMD (from the serving eNB) either to meet the quality of service (QoS) or QoE requirements set by the services run at the tagged MMD, or to improve the current status of its own network, e.g. decongest the radio access network, reduce network interference, or meet certain energy-efficiency requirements. While in the respective geographical area, the network infrastructure of the home operator is sparsely deployed or is under high congestion, the same area may include a plethora of other cellular BSs or Wi-Fi APs. While these BSs/APs can readily support the performance requirements, they belong to different authorities. Aiming to relax this constraint, our proposal here, enables on-the-fly attachment of mobile devices to **any network infrastructure** that can efficiently support their QoS, the QoE or any other requirements set by the operator.

In this example, the serving eNB may not be in the position to support the required QoE at the tagged MMD, while the HeNB1 of the small cell LTE-A operator and the AP1 of the Wi-Fi operator may have surplus of radio resources that can be shared with the macro-cellular operator. Hence, the MMD can measure the signal quality of all nearby cellular BSs or Wi-Fi APs, report back the derived measurements to the serving eNB, and trigger a procedure that will enable it to attach to the most appropriate attachment point(s) even if it is not part of the home operators' network. Therefore, we introduce a controller in this scenario that can enable **on-the-fly instantiation of virtual attachment points** that, on the one hand, the MMD identifies as part of the home operators' network and, on the other hand, run in network infrastructure that is not owned by the home operator. We argue that such an approach can significantly improve the quality of received services by the user and also allow the design of innovative business models among the different network operator domains.

B. Network Architecture

In Table I, we summarize the key features of the main network elements necessary for supporting the proposed resource sharing reference architecture, and further details are explained in this section. Without loss of generality, in Fig. 2 we introduce the proposed reference architecture for the illustrative example discussed in section III-A. Note that the architecture shown in Fig.2 is compliant with the MOCN scenario, i.e. only the RAN is shared among multiple operators, while each operator owns an independent core network. As in the baseline version of the LTE/LTE-A system, the macro-cellular LTE-A network consists of two parts: the radio access network, a.k.a. Evolved Universal Terrestrial Radio Access Network (E-UTRAN), and the core network, a.k.a. Evolved Packet Core (EPC). The E-UTRAN part includes a number of eNBs, whereas the EPC part includes a number of MME entities, a number of Service-Gateways (S-GW), and a single Packet Data Network Gateway (P-GW). The eNBs provide user and control plane protocol terminations towards the User Equipment (UE), whereas the MMEs are responsible for handling the control plane functions for mobility management throughout the mobile operators' network. On the other hand, the S-GWs handle the data plane by routing and forwarding the user data packets towards the P-GW, which in turn is responsible for connecting the remainder E-UTRAN and EPC entities to the Internet.

The small cell network is composed by the E-UTRAN and the EPC part as well. However, different from the macro-cellular network, the E-UTRAN part includes Home eNBs (HeNBs) (instead of eNBs), which are small-sized BSs supporting the same functionality with the eNBs [18]. The Wi-Fi network consists of a number of Wi-Fi APs and Wi-Fi Access Gateways (WAGs). The WAGs are responsible for aggregating the traffic from multiple Wi-Fi APs and handling the Internet connectivity of the entire Wi-Fi network [19]. Note that the presence of a WAG is not mandatory when the Wi-Fi APs are installed by the end users, e.g. the stand-alone AP in Fig.
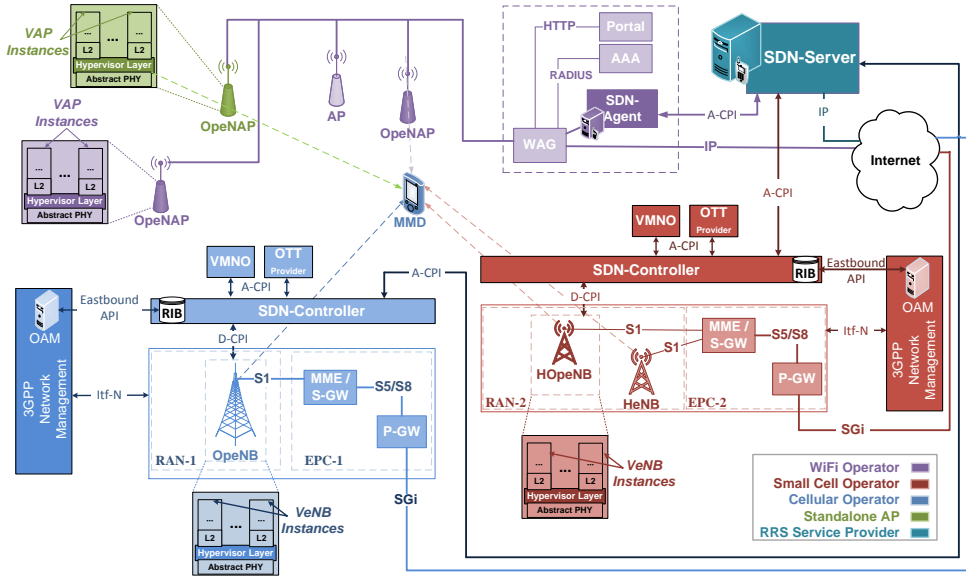
Fig. 2. Reference Architecture.

2. Apart from the aforementioned network entities, support of the proposed RRS service in 5G network, requires functional and architectural enhancements that go beyond the baseline version of the Wi-Fi [20] and the LTE-A network interworking architecture [18]; enhancements are depicted in Fig. 2.

Firstly, we consider that part of the (H)eNBs are endowed with virtualization capabilities that enable them to allocate the surplus of their radio resources to cellular users that are not registered in the same network operator through virtual instances. This type of (H)eNBs, referred to as (H)OpeNBs, employ the OpeNB architecture proposed in [15], that adopts a slightly modified protocol stack compared to the one supported by the legacy eNB. These (H)OpeNBs are capable of abstracting the physical layer (PHY) from the upper-tier layers in the (H)eNB protocol stack and create a common pool of resources that can be shared among multiple tenants. More specifically, a software instance runs on-top of the abstracted PHY to emulate the regular(H) eNBs protocol stack. To achieve this, an additional layer is introduced in between the PHY and the upper-tier layers of the regular (H)eNB protocol stack. This additional layer, referred to as the Hypervisor layer, enables the (H)eNBs to virtualize their physical radio resources, and share them among multiple software instances that run on-top of the PHY. Most importantly, the PHY abstraction (offered by the Hypervisor layer) enables the mobile network operators to adapt their RRS policies on-the-fly and dynamically share their physical network infrastructure (and radio resources) with other network operators (tenants). Another architectural and functional enhancement necessary for coordinating the (fair) resource allocation between multiple operators is the deployment of an SDN-Controller on a per network operator basis. The SDN-Controller handles the resource allocation process among multiple operators that share the (H)OpeNB, with

respect to the a-priori SLA agreements established between the operators (as the Hypervisor proposed in [21]). Moreover the (H)OpeNBs are considered capable of creating multiple software instances of the (H)eNB protocol stack from Layer-2 (L2) and above. Each software instance, which we term as **virtual eNB (VeNB)**, emulates the functionality of a (H)eNB belonging to a different network operator. Moreover, each VeNB can logically inter-connect to the EPC of the home network operator through a Layer-3 (L3) tunnel. Such an approach, not only enables the network operators to dynamically share their under-utilized resources, but also brings the access network closer to the end-user in a dynamic fashion.

Note that the SDN-Controller is a functional enhancement necessary for implementing the proposed RRS service. The SDN-Controller is a logical entity on a per network operator basis that is capable of acquiring a global knowledge of the network state (note that such a knowledge is limited to the local resources of each operator's network) by interacting with the 3GPP Operations Administration and Maintenance (OAM) system via the legacy Eastbound Application Programming Interface (API). More specifically, the OAM provides to the SDN-Controller the status of a number of Key Performance Indicator (KPI), e.g measurements from the MMDs, cell load measurements from the network infrastructure. This information is collected from the RAN via the legacy Northbound Interface (Itf-N)[22]. The collected network information feeds the RAN Information Base (RIB) facilitating a global network view to the SDN-Controller [23][24] . Note that the SDN-Controller interacts with the H(OpeNB) base stations via the Data-Controller Plane Interface (D-CPI) and with over-the-top (OTT) services via the Application Control Plane Interface (A-CPI)[25]. The role of the SDN-Controller is twofold: (1) it is responsible for handling the instantiation of VeNBs at the

(H)OpeNB and adjusting the RRS policies at the Hypervisor layer(s) (via the D-CPI interface) in line with the RRS requests from other network operators; (2) it maintains a global view of the E-UTRAN status by acquiring signal quality measurements from the MMDs, and cell load measurements from the (H)eNB network infrastructure. Such global view enables the SDN-Controller to effectively predict the spatiotemporal availability of radio resources throughout the E-UTRAN infrastructure, and allows operators to implement real-time spectrum auction schemes under the proposed RRS service. It is also important to note that today's MMD are already capable of measuring the signal quality of all BSs (or APs) in proximity [20], [26], independent of whether they belong to the network infrastructure of the home operator.

Similar functional and architectural enhancements are assumed to apply for the Wi-Fi network operator(s). In more detail, we consider that part of the APs are endowed with the virtualization capabilities that enable them to allocate the surplus of their radio resources to Wi-Fi enabled devices that are not (a-priori) registered in the Wi-Fi operator. This type of APs, referred to as OpeNAP, are considered capable of abstracting the physical layer (PHY) from the upper-tier layers of the traditional IEEE 802.11 protocol stack and effectively share the common pool of radio resources among multiple software instances that run on-top the abstracted PHY. In a similar manner with (H)OpeNBs, the OpeNAPs include a Hypervisor layer in between the PHY and the Medium Access Control (MAC) layers. They are hence capable of hosting multiple software instances to emulate the functionality of a regular Wi-Fi AP from the MAC layer and above. In the sequel, we refer to this type of software instances as virtual APs (VAPs). Note that the VAPs are not necessarily required to be logically inter-connected with the WAG of another network operator, unless charging restrictions apply, i.e. when the charging is performed at the home Wi-Fi operator.

Having described all necessary functional and architectural enhancements in the baseline operation of the Wi-Fi and LTE-A networks, we now discuss the key aspects of the SDN-Server entity, depicted in Fig. 2. Even though the SDN-Controller manages the SDN process on a per network operator basis, the SDN-Server is responsible for monitoring and controlling the employment of the proposed on-demand RRS service among the different network domains. In particular, the SDN-Server is the reference point where the RRS among the different network operators is implemented as an **OTT third-party service**. Hence, in this setting, the SDN-Server collects information for the resource availability on a per network operator basis by interacting with the each operator's SDN-Controller via the A-CPI interface (see Fig. 2). The SDN-Server monitors the status of the different network operation domains, hosts all functions necessary for the inter-domain charging, and monitors the implications following from the established SLAs. Note that the SDN-Server acts like the Virtual Resources Manager (VRM) mentioned in [27]. Moreover, the role of the SDN-Server is to act as s third-party entity which regulates the admission control policy of the RSS service

among cooperating network operators. However, differently from the VRM, the proposed SDN-Server is endowed with the capability to regulate handovers among the cooperating operators. The SDN-Server has a global knowledge of resources and information that each cooperating operator puts a disposal of the SDN-Server by means of the local SDN-Controller, according to predefined SLAs. Indeed one home network operator cannot have direct access to confidential information or control any resource of another host operator. An home operator can just request to the SDN-Server, i.e. a trusted entity among the cooperating operators, the RSS service, i.e. a request to the SDN-server to exploit if there is a cooperating operator which has the possibility to offer some of its available resource to the home operator. Note that the SDN-Server acquires a knowledge of the available resource based on the info that are reported by the cooperating operators. Indeed, the SDN-Server does not have access to the resources of any operator. Based on the acquired knowledge, the SDN-server can identify the best host operator to which forward the RSS request of the home operator. Note the final HO decision is always taken at the Host operator side, which finally performs a local admission control and SLA monitoring before to provide RSS service to the requesting home operator. The SDN-Server is also a point where various statistics of network is registered and hence different network analytics can be derived. For example, functionality similar to the Access Network Discovery and Selection Function (ANDSF) server in the 3GPP can run as a service in the SDN-Server and based on the analytics of network. We also foresee the SDN-Server as the regulator of the real-time multi-agent spectrum auction among the participating network operators, defining the price paid by the MMDs upon utilizing the on-demand RRS service. The MMD in our reference architecture is a device equipped with multiple radio interfaces, and is capable of measuring radio signal of all its surrounding radio access, independent of whether they belong to its home network or not. In the device-centric approach, we further assume that the MMD is an autonomous device and present it as an intelligent MMD (iMMD). Functionality of the iMMD is managed by an intelligent agent (running at the device) that is in charge of triggering and control of where to direct its traffic, depending on the measured signal, the network condition reported by the SDN-Controller and the analytics of network reported by the SDN-Server (elements of the ANDSF server). The SDN-Server could also be interfaced directly with the devices through ANDSF server and the 3GPP S14 interface [28]. It is worth to note that the SDN-Controller in each domain can also be used to provide OTT services to Virtual Mobile Network Operators (VMNOs) or OTT providers. As an example, let us assume that a tagged VMNO has established a-priori agreements with a network infrastructure provider (IP1) that owns a set of (H)OpeNBs. The VMNO can request a service via the A-CPI to the SDN-Controller located at the IP1, e.g. it requests RAN coverage for a group of users registered to the VMNO and then, the SDN-Controller handles the instantiation of a VeNB for the tagged VMNO in a number of H(OpeNBs)

as per the pre-established agreement. In addition, the SDN-Controller can offer the RRS service to one or more VMNOs. Upon receiving a RRS request, the SDN-Controller verifies whether the RRS request of the VMNO is in line with the SLA and finally executes the handover of the VMNO users toward a second infrastructure provider (IP2).

IV. CHALLENGES AND OPEN RESEARCH PROBLEMS

In this section, we detail the open issues and research challenges associated with our proposed SDN-based management of the on-the-fly RRS service.

A. Authentication, Authorization and Accounting (AAA)

The proposed SDN-based architecture enables on-the-fly utilization of network infrastructure and resources belonging to different network operators. Nonetheless, a key challenge is where to implement the critical operations of AAA and accounting functions (service charging), given that the proposed RRS service enables MMDs to utilize network infrastructure outside their home operator. Hence, all the involved network entities, including the MMDs, home network operator, host network operator(s), and the SDN-Server at the service provider, should be both authenticated and authorized by a trusted AAA sub-system. The most straightforward solution would be to authenticate all involved parties at the SDN-Server, since it is in a position to check the established SLAs and take all necessary actions for implementing the RRS service. Similar approaches to those used in the mobile IP could be a good starting point for research in this domain [29].

B. Negotiation and Monitoring of SLA

The proposed SDN-based architecture enables different network operators to share their physical infrastructure/resources depending on their users' demand. Nonetheless, the implementation of such a resource sharing service, not only requires control on a per operator basis (similar to the SDN-Controller in our architecture), but also requires the establishment of a-priori SLA agreement between the RRS service provider and operators. Therefore, SLA monitoring and negotiation should be a central part of the proposed RRS service. More specifically, we assume that the SLA negotiation is handled at the SDN-Server, while SLA monitoring is performed either at the SDN-Server either or at the SDN-Controllers. More specifically, the SDN-Server checks whether the requests for the RSS service performed by the operators are in line with the pre-established SLAs, while the SDN-Controller on per operator basis monitors the admission control policy established in the SLAs. On the one hand, SLA monitoring at the RRS service provider is critical for identifying the set of candidate attachment points that a tagged MMD can access. On the other hand, network operators should be able to verify whether an incoming RRS request is in-line with its terms. In either case, several open implementation issues arise, including, frequency of the update on the the established SLAs and the agreed spectrum tariff, by the RRS service provider and the network

operators, the effect of updating frequency on the efficiency and the robustness of the RRS, and finally the trade-off between efficiency and overhead.

C. Real-time adaptation of the spectrum tariffs - Spectrum Auction

Although a long-term SLA with fixed spectrum tariffs is expected to attain a low operational and administration overhead, a real-time adjustment of the spectrum tariffs can enable innovative business models as well as market competition. In this direction, each network operator should be capable of adapting the agreed spectrum tariff with respect to its current network status, e.g. resource availability in a specific geographical region or time interval. On the one hand, the SDN-Server can periodically check changes in the network circumstances and updates the information to the SDN-Controller. On the other hand, the SDN-Controller can implement the auctioning scheme to adjust spectrum tariffs based on the real-time information it receives from the SDN-Server. The effective competition between network operators can potentially improve their revenues while also improving performance by shifting some services to the less congested time periods of the network.

Such approach also advances towards fully competitive spectrum market and provides concrete incentives for active participation in the RRS to the network operators. Nonetheless, as in all markets, market regulation is critical for ensuring that the participants do not form coalitions at the expense of the end user or the RRS service provider. We envisage that the SDN-Controller will participate in such spectrum auction schemes and that the SDN-Server should act as the regulator. Various spectrum auctioning and analytical tools such as game theory that are previously studied in the context of cognitive radio can be reused here to examine optimal regulation and spectrum auction strategies [30].

The concept of spectrum sharing coalitions among tenant operators needs attention as well. There are number of interesting initiatives in this regard, in the literature. In the research work presented in [31], two cooperative game models are proposed to address the competitive spectrum sharing problem: if the tenants in a coalition agree to share its cost but keep their individual revenues, the problem is formalized as a non-transferable utility cooperative game; if the tenants would be willing to give away also part of their individual revenues to be in a coalition, a transferable utility game is proposed instead. Other network sharing and multi tenancy schemes are discusses in [32], [33]. Furthermore, the work in [34] presents a model based on renting and favor.

D. Measurement, Monitoring and Control

Clearly the efficiency of our proposed RRS service heavily relies on the capability of the SDN-Controller in maintaining an up-to-date view of the network, and the capability of the SDN-Server in handling the information exchanged between different network domains. Therefore, frequency of measurements and reporting the measurements by the MMDs, plays

an important role in the performance of the RRS. Building an up-to-date view of different network domains can significantly increase complexity, and overhead in the network, and affect robustness of the RRS service. Therefore, measurement monitoring and control should be carefully designed throughout the entire RRS service chain, i.e. the all operations performed in the network to enable the RRR service, so as to allow the hierarchical exchange of network status information according to highly-efficient and proactive SDN enforcement techniques spanning all network entities involved in the RRS service. While we examine this issue through two different approaches in this paper, the optimal design of measurement monitoring and control still remains an open issue.

E. SDN Enforcement Techniques: Trigger and Control

The SDN enforcement techniques refer to both the triggering criteria and the decision strategies used prior to the employment of the proposed RRS service. As discussed earlier, the SDN enforcement techniques are expected to have a major impact on the reliability and effectiveness of the RRS service due to the large number of entities involved in the RRS service chain. Moreover, triggering and decision phases for the over-the-top RRS service can be based on status of home operator's network as well as status of other network operators. For example, network congestion, energy-efficiency requirements, interference mitigation, the interference caused by an MMD that operates in proximity of a closed access HeNB, and the objective and subjective requirements (i.e. the Qos and the QoE) governing the services run at the MMD can be considered as the decision criteria. In this paper, we discuss two different approaches for triggering and control of our proposed RRS service. One is a device-centric/network-assisted approach, where the RRS is triggered and controlled at the device while benefiting from the global view of the network. In the network-centric approach, we maintain the trigger and control of the RRS at the network while radio measurements are provided by the device. Although we thoroughly examine the pros and cons of the trigger and control placement through these two approaches, the actual optimal placement, that could potentially be a blend of these two solutions, will remain an open question.

F. Resource Provisioning in Admission Control

The performance of the RRS service depends on the admission control strategies employed at the (target) attachment points. On the one hand, traditional admission control strategies will not be in position to anticipate the traffic load from the joint admission of registered and non-registered MMDs. On the other hand, the signaling and administration overheads of a-posteriori rejections of incoming RRS requests, either from the SDN-Controller or the SDN-Server, should also be carefully anticipated. To this end, and in-line with the architecture depicted here, novel admission control strategies can be deployed to further exploit the global network view maintained at the SDN-Server and SDN-Controller entities.
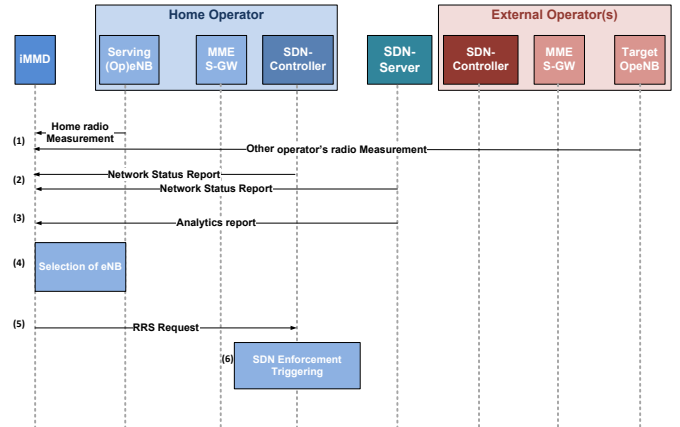

Fig. 3. Signaling in the device centric approach for cellular-only network

V. DEVICE-CENTRIC APPROACH

Today's mobile devices, including smartphones and tablets, have strong computational power. Given their short life time, of less than two years in average, their hardware are often more advanced than those in the access network. Moreover, mobile devices are the best point in the network to make certain decisions on the management of radio and network resources. To this end, device-centric networking gained attention recently [35], which can also act as an enabler for exploiting direct communications between devices [36]. On the other hand, the battery constraint on the device is the major drawback of running complex computations at mobile devices.

In this section, we describe a device-centric approach for radio resource sharing, in which an intelligent agent at the device is in charge of triggering and selecting of where to direct its traffic, depending on the measured signal, the network condition, and Cell Range Extension (CRE) reported by the SDN-Controller and the analytics of network reported by the SDN-Server. The Cell Range Extension (CRE) can make more devices to attach to BS/APs which has less traffic load. Because the CRE can be used to add a positive cell selection offset to the optimal BS/AP. Moreover, the CRE can make devices to be served with BS/APs with low path loss. When devices are closer to BS/APs with less traffic load, the CRE can make devices to avoid selecting BS/AP with higher traffic load, and can reduce the congestion level for the certain BS/AP and energy consumption for devices. For the network analytics, we consider location profiling at the SDN-Server, in which QoS offered by different BSs/APs at different locations are stored, and the details are discussed later in section V-B.

Let us denote by μ_{ik} measurements of user k from BS or AP i and by ν_i network status of the ith BS/AP for $i = 1, ..., I$. In this paper, the considered status of network is congestion at the BS/AP, which is translated into the end-to-end latency and its effect on the throughput. Since multiple criteria identifies

which BS/AP is the most optimum one to connect to and depending on the application, the significance of these criteria for the UE are different, we formulate the problem of where to connect to as a multi-attribute optimization problem under the assumption that UE can connect to any available radio access independent of the access technology and even if the infrastructure belong to a non-home operator.

In Fig. 3 we summarize the signaling flow required to support the device centric RRS service. In step 1, device collects radio measurements from all its surrounding wireless - its home network and other external operators to its own network in the case of cellular-only network as shown in Fig. 3. In the next step device receives the network status (i.e. the network congestion in our case) from the SDN-Controllers. To address the scalability issue and not introducing extra overhead as number of devices increases, such information can be transmitted via multicast or broadcast mechanism to the devices. The status of the external operators will be delivered to the device through SDN-Server. This step will follow by step 3 in which network analytics are acquired from the SDN-Server. Step 4 will use the information collected in the first three step to make a decision on where to connect to, based on the algorithm explained in section V-A. After such decision is made, device will request for the trigger of the appropriate RRS service from the SDN-Controller of the home operator. The remainder of procedure from step 5, including the instantiation of the virtual entities, are supported via the network, and explained in the next section.

A. Multi-Attribute optimisation problem

The selection of BS or AP at the iMMD based on measurements and/or network congestion (provided by the SDN-Controller) is modelled as a Multi Attribute Decision Making (MADM) process. In this implementation, we use *Analytic Hierarchy Process* (AHP) to calculate weight values for each selection criteria (depending on the application), and *Technique for Order Preference by Similarity to Ideal Solution* (TOPSIS), for selecting the optimal BS/AP - the combination of AHP and TOPSIS have previously used for network selection in [37]. The TOPSIS belongs to classic MADM techniques, which selects the best alternative (in this case, e.g. the best BS/AP) based on multiple attributes, as the solution, and has shown to find the optimal solution. This class of MADM techniques are used most commonly for network selection [38]. Finding the best alternative is based on finding the candidate with the shortest distance from the best possible solution, while having the longest distance from the worst possible alternative. Our implementation follows five steps as below.

1) *Constructing the decision matrix for TOPSIS*: For any given application, the decision matrix is $C = [c_{ij}]$, where c_{ij} represents rating of the Alternative i (certain access point), with respect to delivering attribute j (certain QoS parameter).

2) *Constructing weighted normalized decision matrix*: The decision matrix is normalized, as $V_{norm} = [v_{ij}]$, where

I is the total number of alternatives.

$$v_{ij} = \frac{c_{ij}}{\sqrt{\sum_{i=1}^{I} c_{ij}^2}}, \qquad (1)$$

We then calculate the weighted normalized decision matrix, $D = [d_{ij}]$, which can be shaped by multiplying v_{ij} by the W_j - the weight values of W_j for each application are computed by the AHP and the values we use for our performance studies are detailed in Table II, and are based on the values computed in [39].

3) *Determining the negative and positive ideal solutions*: The negative and positive ideal solutions, i.e. A_i^- and A_i^+, are the best and worst alternative (based on weighted decision matrix) and can be described as Equations (2) and (3). For criteria with the lower band (i.e. desired values such as throughput), A^- and A^+ can be expressed as:

$$\begin{aligned} A_i^+ &= \max_i(d_{ij}) \\ A_i^- &= \min_i(d_{ij}). \end{aligned} \qquad (2)$$

while for the undesired values such as delay or network congestion, A_i^- and A_i^+ can be expressed as:

$$\begin{aligned} A_i^+ &= \min_i(d_{ij}), \\ A_i^- &= \max_i(d_{ij}). \end{aligned} \qquad (3)$$

4) *Calculating Euclidean distances to positive solutions and negative solutions*: In step 4, Euclidean distances of alternative i to the positive and negative ideal solutions are computed as below:

$$\begin{aligned} S_i^+ &= \sqrt{\sum_{j=1}^{J}(A_i^+ - d_{ij})^2}, \\ S_i^- &= \sqrt{\sum_{j=1}^{J}(A_i^- - d_{ij})^2}. \end{aligned} \qquad (4)$$

where J is the total number of attributes.

5) *Ranking the preference order*: Finally, results are compared according to the Equation (5) and the maximum value of τ_i is selected as the optimal result.

$$\tau_i = \frac{S_i^-}{S_i^- + S_i^+} \qquad (5)$$

In this case, the selected i, the one with the maximum value of τ_i, represents the BS/AP, selected by the iMMD, and offering the best QoS for its running application - in other words the best QoE to the user. Note that different quality parameters had different weights, W_j, for any given application. If the selected BS/AP is not a home network, SDN-Controller will run the RRS service, i.e. instantiate the V-AP/VeNB, so that the connection could be considered as part of the home network.

B. Considering the Network Analytics

As mentioned earlier, in addition to the network status and radio measurements, the best BS/AP could be selected based on some network analytics (hosted at the SDN-Server). Here, we argue that location profile is a valuable information

in deciding which network can carry my traffic better. In a nutshell, if we know what was the experience of previous users standing in the current location of the device, and which radio access they were connected to, we can potentially make a decision only based on that.

Let for device l the location profile be P_l in which, each row represents information of one specific location, i.e. current location is in the first column (denoted by Δ), and then pair values of goodput (goodput is considered to address both throughput and delay) and BS/AP identification, denoted by (g, η).

$$P_l^{m,1} = \Delta_m, \quad for \; m = 1...M. \tag{6}$$

$$P_l^{m,t} = (g, \eta)_{m,t}, \quad for \; m = 1...M \; \& \; t = 1...T. \tag{7}$$

where M and T identifies total number of location profile we store. For simplicity of communication between SDN-Server and the iMMD, and also for privacy issue, we assume, server can send only two anonymous rows from the profile to the device. Those two rows corresponds to the BS/AP that offered best and worst experience in the ten meter vicinity of the device. We then use these two values in Equation (4) and instead of the A^+ and A^-. Therefore, we find the solution based on having furthest distance from the worst experience recorded in the profile, and having the closest distance to the best past experience. Using such location profile adds zero complexity to the selection of BS/Ap since it only replace values in one of the steps of the algorithm. Clearly more advance location profile can be used to further improve the achieved performance.

C. Location Profile and Location Estimation

As mentioned in Section IV, fine-grained monitoring and measurements are among the main open challenges in the design of the RRS as a service. In the case of location profile also, if information is up-to-date and relevant to the current location of the device, traffic will be directed to the radio access in an optimal fashion. On the other hand, frequent updating of the information is costly. A more specific issue here, is how device monitors its locations. In outdoor scenarios, GPS provides a relatively precise estimation of the device's location but with an extra cost of battery. In indoor scenarios, however, such precision doesn't exist and various methods for positioning of the device are explored in the literature. With the large deployments of the WiFi APs, WiFi fingerprinting is one of the interesting directions in this area [40]. In fact, many commercial buildings exploit WiFi fingerprinting for customized advertising to their visitors. Both location estimation and up-to-date location profiles as well as the cost associated to them, are open to further investigations.

VI. NETWORK-CENTRIC APPROACH

In this section we outline the network-centric approach. In this approach the SDN Enforcement Techniques are employed at the SDN-Controller and SDN-Server entities based on measurement feedback provided by the access network elements (including the device). Hence, the network-centric approach can be viewed as an device-assisted network-controlled approach. In this approach, the role of the MMD is to provide the home operator's SDN-Controller, i.e. Home SDN-Controller, with up-to-date measurements on the received signal from all nearby radio. Note that these measurements can be also collected by the SDN-Controller via a directly interaction with the OAM. Recall that the MMD is considered capable of measuring the signal level from attachment points not necessarily belong to the home operator (Section III). Under the network-centric approach, the employment of signal measurements at the MMD is monitored and controlled by the Home SDN-Controller. The Home SDN-Controller is also responsible for triggering the RRS, i.e. initiate RRS service request towards the SDN-Server, if a prescribed set of SDN Enforcement conditions apply. For example, the SDN Enforcement triggers can relate to the QoE perceived by the user, the QoS constraints inherent to the user services, or the network status. The RRS service request should include adequate information to enable effective SDN Enforcement Decisions at the SDN-Server side. Such information may refer to the attachment point in which the MMD is currently attached, the list of measurements on other attachment points (as reported by the MMD), and in general, the conditions that led the Home SDN-Controller to trigger the RRS service request, e.g. network status and load. Upon receiving the RRS service request, the SDN-Server is subsequently responsible for acting as the reference point for initiating the RRS service and orchestrating the different network domains (and operators) involved. In particular, the SDN-Server should be able to:

1) authenticate and authorize the Home SDN-Controller
2) verify that the respective RRS request is in line with the established SLAs
3) choose the most appropriate (target) attachment point for the tagged MMD
4) forward the RRS request to the SDN-Controller that is responsible for handling the respective attachment point - owner of the target attachment point is named as the Host Operator

Upon receiving the RRS request, the SDN-Controller at the Host Operator, i.e. Host SDN-Controller, should verify that the RRS request is in line with the established SLAs and take all necessary actions for supporting the incoming RRS request (if valid). For example, the Host SDN-Controller should trigger an admission control phase at the target attachment point and create an appropriate software instance, VeNB/VAP, for supporting MMDs belonging to Home Operator. If the Host Operator is capable of supporting the incoming RRS request, the Host SDN-Controller informs the SDN-Server that it can admit the tagged MMD and the ongoing services will be transferred to the target attachment point. Depending on the type of RATs supported by the Home and the Host operator, a direct tunnel between the two different network domains can be established so as to better support the proposed RRS service.

A. Signaling Flow

In Fig. 4 we summarize the signaling flow required to support the proposed RRS service in the cellular-to-cellular RRS scenario, where both Home and the Host Operators are LTE-A network operators. Since some of the signals in Fig. 4 are common for all RRS service request, i.e. independently of the MMD under scope, they can be performed only once, e.g. when the RRS service is initiated for the first time between the respective Home and Host Operators. As discussed in section III, the Home SDN-Controller is responsible for monitoring the status of the MMDs as well as the access network elements that belong to the home network operator. Based on the employed strategies for monitoring, measuring and control (MMC) (step 1), the Home SDN-Controller configures the serving eNB of the tagged MMD to (periodically) report its status and to configure the measurement process at the attached MMDs (step 2). The serving eNB configures the MMD to perform signal measurements on the status of all nearby attachment points in a periodic or event-driven fashion [26] (step 3). Note that in the LTE-A system, the derivation of signal measurements at the end terminals is always controlled by the serving eNB.

Accordingly, the MMD measures the signal quality from all nearby attachment points (step 4) and reports back the measurements to serving eNB (step 5). This information can be accessed by the SDN-Controller via the OAM as described in section III. Note that for the sake of simplicity, in the sequel we assume that such information is logically provided by the eNB to the SDN-Controller, however we assume that the SDN-Controller is capable to acquire such information directly by the OAM, e.g. current staus of the MMD, cell load (step 6). Based on these measurement, the SDN-Controller subsequently checks if the pre-set SDN Enforcement triggers are met and, if needed, initiates a RRS request towards the SDN-Server. To achieve this, the Home SDN-Controller is firstly authenticated and authorized by the SDN-Server (step 8). Note that this step can be omitted if the connection between the SDN-Controller and the SDN-Server has been already identified as a trustyworthy one. Upon receiving the RRS service request (step 9), the SDN-Server subsequently verifies that it is in line with the established SLAs (step 10) and identifies the most appropriate attachment point for the tagged MMD (step 11). Note that in this step, the SDN-Server may combine various inference methods and criteria to conclude on the most appropriate attachment point for the inbound RRS service request (see Section III).

Having identified the most appropriate attachment point, i.e. the target OpeNB in Fig. 4, the SDN-Server subsequently notifies the Host SDN-Controller for the pending RRS service request (step 12). In the sequel, the Host SDN-Controller verifies that the respective request is in line with its view of the RRS-related SLAs (step 13), and commands the target OpeNB to check the availability of local radio resources (step 14). Note that the SDN-Controller may be required to authenticate the SDN-Server in this step as well, and vice versa. Upon

receiving the RRS command, the target OpeNB performs admission control and, if successful, creates a VeNB instance to emulate the operation of a regular eNB belonging to the Home Operator (step 15). Note that the VeNB instantiation can be omitted if the target OpeNB already hosts a VeNB instance for the respective Home Operator. This step enables scalable support of the proposed RRS service in a transparent fashion for the tagged MMD.

In the steps 16-18, all intermediate core network elements involved in the RRS service chain (i.e. up to the Home SDN-Controller), are informed on the successful completion of all steps at the Host Operator. The SDN-Server initiates the establishment of a direct tunnel between the Home and the Host Operators to enable the transfer MMD's connection. Furthermore, this step enables the direct exchange of handover-related signals between the two different network domains as well (step 19). Alternatively, to further reduce inter-domain signaling and network management overheads, e.g. end-to-end handover execution delay, the VeNB instance can be attached to the core network of the Home Operator through a logical interface, e.g. over an L3 tunnel. Afterwards, the SDN-Controller triggers the serving eNB to initiate a handover execution for the tagged MMD (step 20), and the serving eNB commands the MMD to attach to the VeNB that is hosted at the target OpeNB (steps 21-22). Since the VeNB emulates all upper-layers in the eNB protocol stack, the MMD should be able to attach to the target VeNB in a transparent fashion. Note that in Fig. 4, we have adopted the make-before-break signaling approach, as we reserve all necessary resources at the Host Operator's network prior to breaking the existing link of the MMD with the Home Operator's network.

B. SDN Enforcement Techniques

In this section we discuss possible strategies for triggering and controlling the RRS service in network-centric approach.

RRS Service Triggering: We start with the SDN Enforcement phase that is executed in step (7) by the Home SDN-Controller (Fig. 4). Firstly, we note that handover triggering is integral part of the traditional handover execution procedure in LTE/LTE-A, where the received signal strength at the UE, or the cell load, are compared to thresholds. The key difference of our architecture, is that the set of candidate eNBs is enriched with the set of attachment that are in proximity of the tagged MMD. The RRS service triggering phase should be left open to the network operator RRS strategy, i.e. implementation-dependent, so as to enable the employment of operator-driven network management strategies. In the following, we propose two simple exemplary RRS service triggering algorithms: the NV-RSRQ and the NV-Offloading algorithms.

In the NV-RSRQ algorithm, the SDN-Controller triggers the RRS service based on the Reference Signal Received Quality (RSRQ) measurements performed by the tagged MMD (step 5). Under this viewpoint, the MMD reports the RSRQ of all BSs/APs in proximity. Depending on whether the BS/AP with the highest RSRQ belongs to the home operator or to another operator, the serving eNB employs standard handover deci-
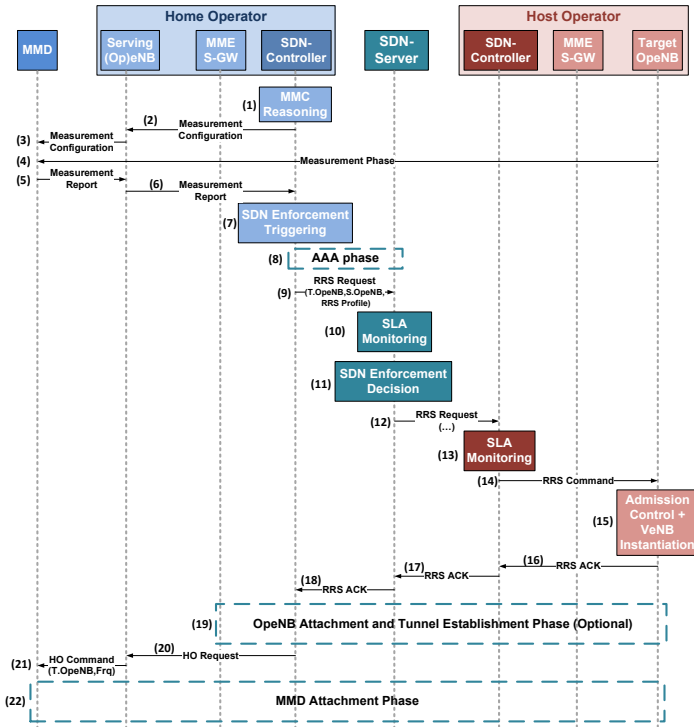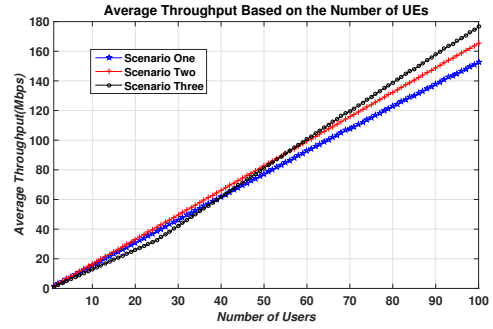
Fig. 4. Signaling in the network centric approach for cellular-only network.

(a) Total average throughput for UEs

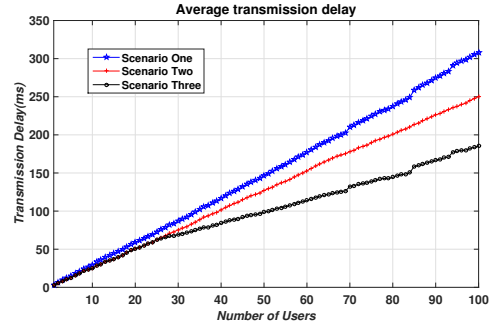(b) Total average delay for UEs

Fig. 5. Device-Centric Approach.

sions, or the RRS service in initiated by the SDN-Controller towards the SDN-Server and indicate the OpeNB with the highest RSRQ value. In the NV-Offloading algorithm, the SDN-Controller triggers the RRS service based on its cell load, i.e. if load at the serving eNB is lower than a threshold, the serving eNB handles the execution of handover as in the traditional scenario. However, if the cell load at the serving eNB is higher than a prescribed threshold, the serving eNB can trigger the MMD to perform RSRQ measurements for all attachment points in proximity.

The NV-RSRQ algorithm is expected to achieve significant performance improvements at the MMDs, since it enables them to connect to the BS/AP providing the most favorable signal quality conditions. At the same time, this can be the cause of increased leasing costs for the home operator as well as excessive traffic offloading towards the network of other operators. In the contrary, the NV-Offloading algorithm is expected to compensate these weaknesses as it initiates the RRS service only if the serving eNB is overloaded. Such an approach is expected to lower the number of RRS service request in a network-wide scale and reduce leasing costs.

RRS Service Control (Decision): The SDN Enforcement phase is executed in step (11) by the SDN-Server (Fig. 4), in which, the SDN-Server identifies the most appropriate attachment point for the tagged MMD by considering the OpeNBs belonging to other operators as well. To complete this phase, the Home SDN-Controller should provide the SDN-Server with all information required to take the SDN Enforcement decision. Such information may include the characteristics of

the ongoing MMD services, the list of measurements reported by the MMD, the triggers that initiated the RRS service request, the load status at the serving eNB, the identity of the MMD, and so on. In the remainder of this paper, we consider that the SDN-Server employs an RSRQ-based selection of the most appropriate attachment point. In more detail, we consider that, upon receiving a RRS service request, the SDN-Server forwards the RRS service request towards the OpeNB that attains the highest RSRQ in the list of reported measurements (for the tagged MMD).

VII. PERFORMANCE EVALUATIONS

In this section, we discuss performance examination of the two different resource sharing approaches. All results are based on simulations. In the first part, the device-centric approach is studied in a smaller scenario since the focus is on the optimization algorithms running at the device. In the second part we focus on system-level performance of the network-centric approach for a larger scenario.

A. Device-centric Approach

We examine the device-centric resource sharing approach in a network scenario consisting of one LTE Macro cell, one pico, one femto, and one WiFi access point. We assume coverage area of the three latter access points is included in the coverage area of macro cell. The QoE offered by these BSs/APs is a random value within the range listed in Table II. The required values by each application are also listed in Table II, based on the values in [41], [42]. As explained earlier, we used the

Parameter	Value
Range of Throughput offered by WiFi	11-54 (Mbps)
Range of Delay offered by WiFi	100-200 (ms)
Range of Throughput offered by LTE femto	10-100 (Mbps)
Range of Delay offered by LTE femto	50-100 (ms)
Range of Throughput offered by LTE pico	10-100 (Mbps)
Range of Delay offered by LTE pico	50-100 (ms)
Range of Throughput offered by LTE macro	10-100 (Mbps)
Range of Delay offered by LTE macro	50-100 (ms)
Path loss model	$L = 128.1 + 37.6 log10(R)$ [15.s]
Requirements (Throughput & Delay) of Video Application	500-700 (Mbps) & 200-300 (ms)
Requirements (Throughput & Delay) of Interactive Application	300-600 (Mbps) & 100-300 (ms)
Requirements (Throughput & Delay) of Peer-to-Peer Application	700-1000 (Mbps) & 300-600 (ms)
Requirements (Throughput & Delay) of E-service Application	600-800 (Mbps) & 50-100 (ms)
Weights of Throughput and Delay for Video Application	0.0909 & 0.4545
Weights of Throughput and Delay for Interactive Application	0.6000 & 0.2000
Weights of Throughput and Delay for Peer-to-Peer Application	0.6479 & 0.1222
Weights of Throughput and Delay for E-service Application	0.3333 & 0.3333

Fig. 6. Reduction in the Signalling Overhead

AHP to weight the parameters for each application, as listed in Table II, which are based on Saaty's scale.

There are 100 UEs, uniformly distributed in the full coverage area of the macro cell, i.e. a circle with diameter of 500 meters around the macro cell, the other three BSs/AP are randomly placed. Each of the 100 users are allocated to run a single application while equal number of UEs run each type of application (25 UEs run each of the applications). We assume that the locations of UEs at 10 different time steps are randomly generated using uniform distribution in the range of (0,500). The requirements of different applications are also randomly generated, based on uniform distribution within the range listed in Table II. Presented results are the average 10 runs of the simulation. However, the deviation among results of different runs were insignificant. The wireless channel is modeled only with path loss, detailed in Table II.

We run three simulation scenarios. The first one, which will later act as a benchmark for the latter two runs only based on the measurements at the device. In other word, the first scenario is soley a device-centric scenario, hence scenario one is DC scenario. The second one simulates the device-centric/network-assisted (DC/NA) scenario in which in addition to measurements, network view (for example congestion at different BSs) and operator's policies are also taken into account. Random values in the range of $[10MB - 50MB]$ represent the congestion level at each BS/AP. We translate the network congestion to delay that can affect the end-to-end throughput respectively (a simple queuing model is assumed here). The third scenario however, introduce using of the network analytics, in the form of location profiles, based on which the best BS/AP can be selected (detailed in section V-B). Therefore, the third scenario can be seen as the device-centirc/network and analytic assisted (DC/N&AA) scenario.

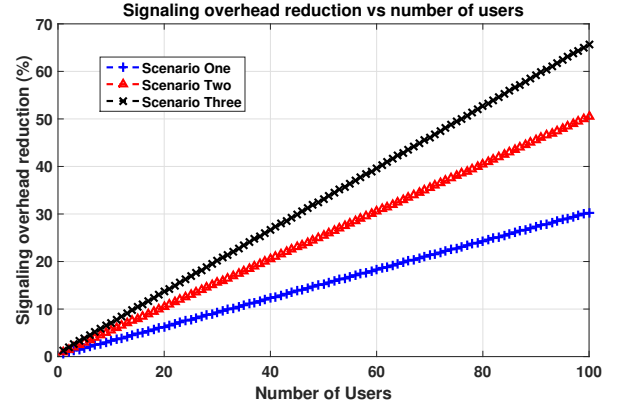Fig. 5(a) and 5(b) show the aggregated values of average throughput and average delay per user in the three simulated scenarios. Observing from these two figures, moving from the first scenario that is DC only to the second and third scenario that are DC/NA and DC/N&AA, there is a small improvement in the throughput but a significant reduction in latency. This is mainly due to the fact that extra information on network congestion is integrated in the selection process in the two latter scenarios. We can therefore argue that the enhancement on the end-to-end throughput (i.e. the goodput) is more significant in the DC/NA and DC/N&AA scenarios.

While the improvement in terms of latency and throughput are not significant, we can see further enhancements in terms of battery consumption at the mobile devices and also in terms of signalling overhead. Observing from Figure 6, it can be seen that singling overhead is reduced to less than half. Also, Figure 7 shows that extra saving of up to 40% can be achieved in the battery consumption of the mobile devices.

We also look into the balance of load between different BSs/APs in these three scenarios. Fig. 8-10 shows the number of UEs connected to each of the BS/AP at nine random time stamps throughout the simulation. These three figures show how having the network information in scenario two could provide better balance of traffic distribution between BSs/APs, while relying only on the radio signal measurements could results in potential congestion at some of the BSs/APs (the effect of which was seen in Fig. 5(b)). The average values of standard deviation between number of UEs connected to each BS/AP in each of the three scenarios, denoted by $\bar{\delta}$, is $\bar{\delta} = \{20.23, 17.91, 13.65\}$. Further observation from these three figures reveal that in the third scenario, since the decision on where to connect to is made based on long term statistics, number of UEs who change their connected point throughout different time stamps of the simulation are less than the other two scenarios.

In summary, it can be seen that using the multi-objective optimizations (AHP and TOPSIS) at the device, enable mobile devices to make optimal network selection based on their QoS requirements. While the enhancements in terms of throughput and latency is not significant, further enhancement in terms of signalling overhead and battery consumption at the devices
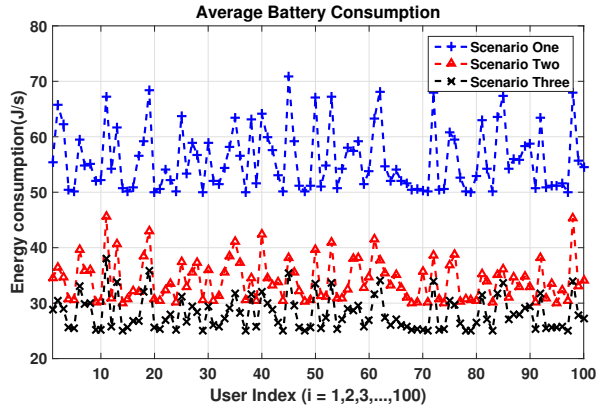
Fig. 7. Users Average Battery Consumption

Fig. 10. Balance of loads between different BSs/APs in the DC/N&AA scenario (scenario three) at selected time stamps.
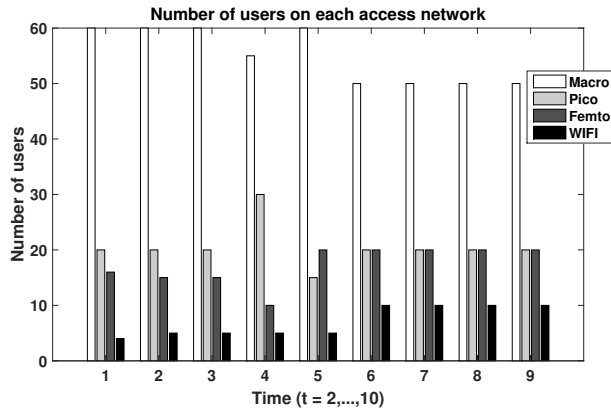

Fig. 8. Balance of loads between different BSs/APs in the DC scenario (scenario one) at selected time stamps.
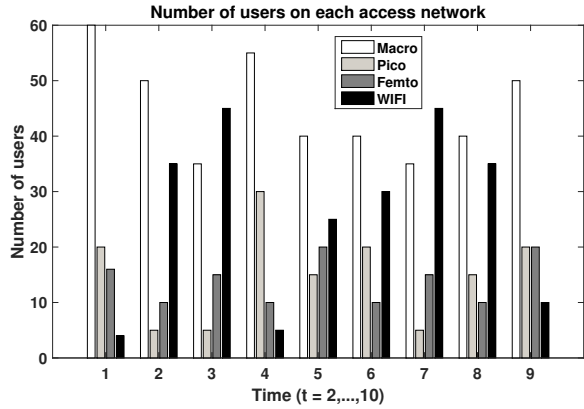

Fig. 9. Balance of loads between different BSs/APs in the DC/NA scenario (scenario two) at selected time stamps.

are introduced.

B. Network-centric Approach

In this section, we present system-level simulation results of the proposed RRS under the network-centric approach in the LTE/LTE-A network, using LTE-Sim simulator [43]. In our simulation setup, we assume that the 5G radio resource
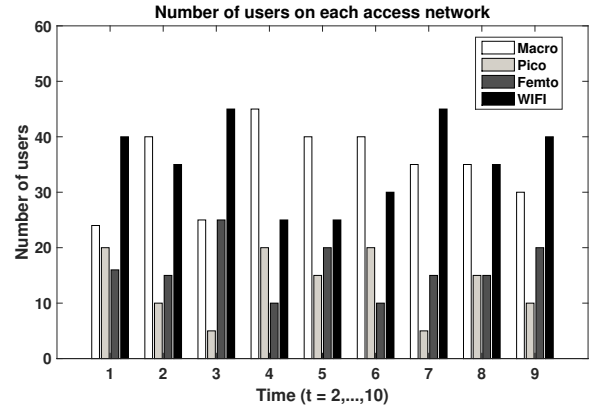
management is provided as a service. We consider a geographical area that includes two overlapped LTE-A networks owned by two different operators: Operator A (acting as home OPERATOR) and Operator B (acting as host OPERATOR). The network of Operator A consists of 7 macro cells with inter-site distance of 1 km, while the network of Operator B consists of 7 macro cells that overlap the coverage of the macrocell network of Operator A. We assume that Operator A use only legacy base stations, i.e. not endowed with virtualization capabilities. We further consider that Operator B owns a number of femtocells that are uniformly distributed within the coverage of the macrocells owned by Operator B. We use the 3GPP 5×5 grid model [43] for the locations inside the buildings of a suburban area. We assume that each building contains five femtocells that are uniformly distributed within the apartments. The number of buildings is adapted depending on the desired femtocell density in the network and is used as the x-axis parameter in our simulations. We also assume that all base stations of Operator B support the OpeNB functionality and operate in the same frequency. Fixed number of pedestrian UEs are uniformly distributed within the coverage area of each eNB operated by either A (40 UEs/ eNB) or B (30 UEs/ Macro Cell). The presented results are derived assuming each UE sustains an H.264 video flow encoded at 440 kbps with a maximum delay constraint of 100ms. The rest of simulation parameters are in Table III.

We will refer to the first scenario as the baseline scenario, where the proposed RRS service is not employed. More specifically in the baseline scenario, we assume that the users registered to the operator A are free to move in the macro-cell network of A. Indeed, it can be handed over to the Macro BS with the best RSRQ. Note that no intra-operator offload mechanisms are taken into account for the operator A, as the aim of our simulation campaign is to evaluate the potential gain of an inter-operator offload mechanism based on the proposed RRS service. Depending on the triggering and admission control algorithms adopted, we examine the performance of the proposed RRS service under two different

Parameter	Value
Number of eNBs (Home Operator)	7
Inter-site distance (Home Operator)	1km
Total Bandwidth (Home Operator)	10MHz
UE Density (Home Operator)	40 UEs per eNB
Number of OpeNBs (Host Operator)	7
Inter-site distance (Home Operator)	1km
Total Bandwidth (Home Operator)	10MHz
UE Density (Host Operator)	30 UEs per eNB
Distribution of buildings per OpeNB (Host Operator)	Uniform (0 to 40)
Distribution of HOpeNBs	Uniform inside the building (up to 1 HOpeNB per apartment)
Number of HOpeNBs	5 HOpeNBs per building
Mobility Model	Random Way Point Model [43]
UE speed	Pedestrian (3 km/h)
Path Loss Model	$L = 128.1 + 37.6 log10(R)$ [43]
Fading Model	Jakes Model [43]
DL Scheduler	MLWDF [43]
Application Traffic Model	Video Streaming encoded at 440 kbps

scenarios. In the NV-RSRQ scenario, we employ the NV-RSRQ algorithm for the RRS triggering phase. It has been considered that the OpeNBs accept all the RRS requests from Operator A in the admission control phase, as long as the target OpeNB has enough resources to satisfy the QoS requirements of the requests. In the NV-Offload scenario, we employ the NV-Offloading algorithm and assume that the target OpeNBs accept all RRS requests from Operator A, as long as its load is below a prescribed threshold.

Fig. 11(a) shows the average goodput of the UEs, i.e. the throughput as measured at the application layer, that are registered to the home operator for all scenarios vs. the number of femtocells in the host operator. It can be seen that the UE goodput performance for all scenarios that employ the proposed RRS service, i.e. the ones with the prefix 'NV-...', outperform the UE goodput performance in the baseline scenario. This trend directly follows from the fact that the employment of the proposed RRS service enables the cellular UEs to connect to cellular BSs with more favorable channel conditions, e.g. higher RSRQ, or the lower path loss. Notably, we observe that the employment of the proposed RRS service, not only improves the goodput performance of the UEs that are offloaded to Operator B, but also improves the performance of the UEs that continue to receive service from Operator A. In fact, the performance of the UEs that continue to receive service from Operator A is improved at a higher rate compared to those offloaded to Operator B. This follows from the fact that the proposed SDN-based solution enables traffic offloading towards the host operator, leaving more resources for the UEs that continue to receive service from Operator A.

Further observations show that the highest performance gains are achieved in the NV-RSRQ scenario. This behavior follows from the fact that the NV-RSRQ triggering algorithm favors the execution of handovers towards the BSs with better channel conditions. We first observe that the goodput performance of the UEs offloaded to Operator B are roughly the same for the NV-Offload scenario (as compared to the

one for the NV-RSRQ scenario). On the contrary, a slightly better performance is observed for the UEs that continue to receive service from Operator B in the NV-Offload scenario. Interestingly, under low femtocell densities (left side of the plot), the performance of the UEs offloaded to Operator B, under the NV-Offload scenario, is higher compared to that of the UEs that continue to receive service from Operator A. However, this behavior alters in higher femtocell densities, where an increased number of UEs from Operator A can be offloaded to the femtocells of Operator B, leaving more resources for the UEs that continue to receive service from Operator A.

Let us now examine the average goodput at the UEs that are registered in Operator B (Fig. 11(b)). As expected, the employment of the proposed RRS service reduces the average goodput at the UEs registered in Operator B, as a result of the increased demand of network resources. This observation readily follows by comparing the performance of the baseline scenario to that of the NV-based scenarios. Fig. 11(b) also reveals that the highest gains at the UEs of Operator A (NV-RSRQ in Fig. 11(a)) are attained at the cost of higher performance losses at the UEs of Operator B (NV-RSRQ in Fig. 11(b)). Nevertheless, this mainly follows from the fact that the NV-RSRQ scenario assumes that the OpeNBs do not perform admission control at the Operator B. Therefore, employment of load-balancing based criteria during the RRS triggering and admission control phases can result in notable performance gains for the UEs registered to Operator A (Fig. 11(a)) without significantly deteriorating the performance of the UEs registered to Operator B (Fig. 11(b)).

In Fig. 12(a), we plot the average downlink signal to interference plus noise ratio (DL SINR) for the UEs registered to the home operator (averaged over all users). As the number of femtocells increases, an enhanced DL SINR is experienced at the UEs registered to Operator A, including both the ones that continue to receive service from Operator A and the ones that are offloaded to Operator B. Similar to Fig. 11(a), the highest performance gains are shown for the NV-RSRQ scenario (close to 1.5 dB), while also notable performance gains are observed for the NV-Offloading scenario (close to 1.2 dB). It is important to remind the assumption on the same operating frequency for macrocell and the femtocell of Operator B. Hence, even higher performance gains would be expected if the femtocell and macrocell base stations in Operator B utilized different frequencies.

In Fig. 12(b), we plot the average DL SINR for the UEs registered to the host operator, vs. femtocell density. As expected, the admission of additional UEs in Operator B, reduces the average DL SINR for all UEs registered to Operator B. Nevertheless, performance gains for the UEs registered to the home operator (Operator A) is comparably lower than the loss on the UEs in the host operator. The NV-RSRQ scenario is shown to reduce the average DL SINR at the UEs registered to Operator B by up to 0.5 dB, while the NV-Offloading scenario performs worst than the baseline scenario.

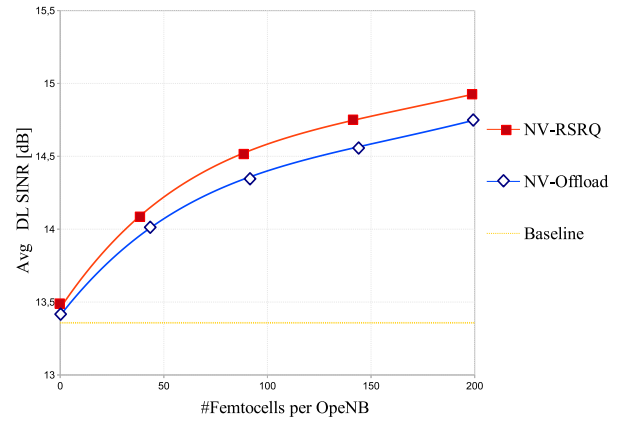Fig. 13(a) depicts the average end-to-end delay experienced
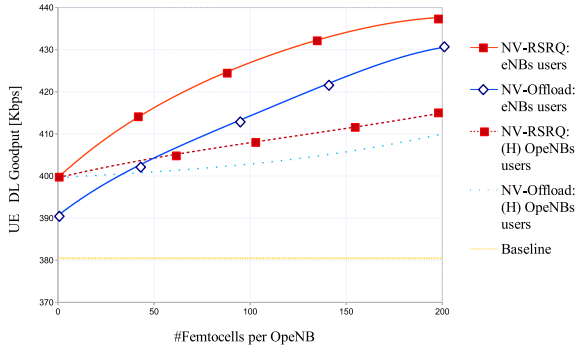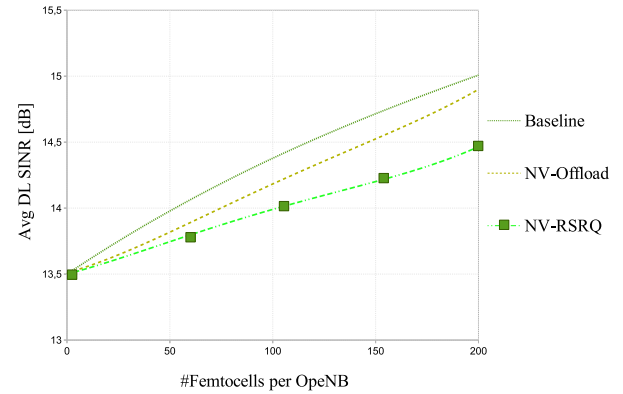
(a) UEs registered to Operator A
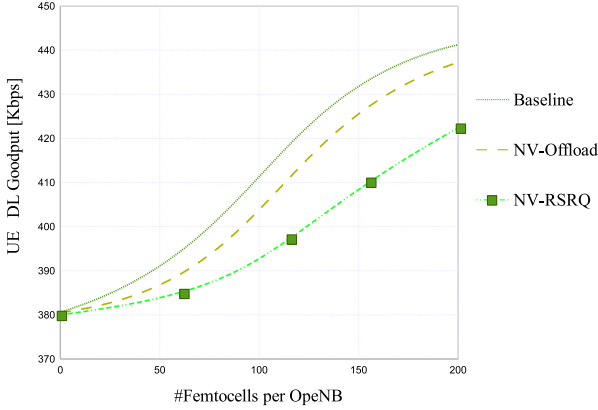
(b) UEs registered to Operator B

Fig. 11. Average DL Goodput for UEs.

(a) UEs registered to Operator A

(b) UEs registered to Operator B

Fig. 12. Average DL SINR for UEs.

by the UEs registered to Operator A, as measured at the application layer. It can be seen that the employment of the proposed NV-based architecture significantly reduces the end-to-end application-layer delay at the UEs registered to Operator A for all NV scenarios. Further observations reveal that the performance gains are proportional to the number of femtocells available from the host operator (B). Fig. 13(a) also shows that the end-to-end application-layer delay at the UEs is roughly the same for all the NV scenarios when the femtocell density at the host operator is medium to high, i.e. higher than 160 femtocells per macro OpeNB. An interesting conclusion is that apart from increased goodput at the application layer (Fig. 12(a)), the employment of the proposed SDN-based architecture results in substantial reduction of the end-to-end application-layer delay at the UEs (Fig. 13(a)). This reduction reaches up to 60% as compared to the baseline scenario. Such performance gains can significantly enhance the experience of the end-user, upon reception of delay-sensitive services, fully capitalizing the performance gains following from using SDN in the access network of the LTE system. It should be noted that the performance improvement, in terms of end-to-end application-layer delay, not only follow from the enhanced goodput attained at the UEs (Fig. 12(b)), but also from the flexibility that enables the UEs to associate with the closest

base station in proximity. Besides, in lower loads, the packet scheduler at the BSs of the home operator can better handle the packet flows of the UEs that remain in the home operator. This effect further reduces the queue processing time, decreasing the overall packet delivery latency as well.

Let us now examine the effect of NV scenarios on the end-to-end application-layer delay of the UEs registered to the host operator through plots in Fig. 13(b). As expected, this delay is reduced for the higher femtocell deployment densities in all scenarios. Interestingly, even though the employment of the proposed RRS service is shown to increase the average delay for the UEs registered to B, as the femtocell deployment density increases, this performance deterioration is compara-bly smaller than the performance gains attained at the UEs registered to Operator A (Fig. 13(a)). The employment of the NV-RSRQ scenario, which has been shown to provide up to 21 ms reduced delay for the UEs registered to Operator A, is shown to increase the end-to-end delay at the UEs registered to Operator B by up to 9 ms. On the other hand, the performance of the NV-Offloading scenarios is shown to be roughly the same as compared to the baseline scenario (up to 2ms increase of the end-to-end delay). It is also important to note that the

(a) UEs registered to Operator A

Fig. 14. Average network load.
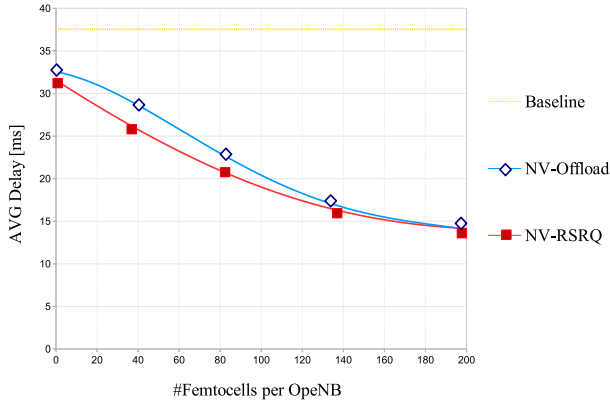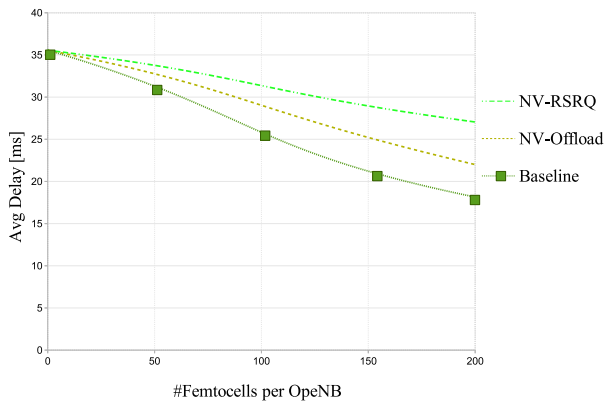
(b) UEs registered to Operator B

Fig. 13. Average latency for UEs.

Fig. 15. Handover signaling rate

performance deterioration at the UEs of Operator B will leave their QoS performance unaffected, since the maximum delay requirement for the assumed traffic type, i.e. delay-demanding video streaming, is 100ms.

In Fig. 14, we plot the average network load at the home and the host operator. We assume 280 UEs are registered to Operator A and 210 UEs are registered to Operator B. As anticipated in the previous results, the NV-RSRQ scenario allows the home operator to offload a higher number of UEs to the host operator, i.e. up to 25% of the served UEs. This is due to the fact that the RRS triggering algorithm employed at this scenario favors a higher number of RRS requests towards the host operator. However, this results in an up to 34% increase of the traffic load at the host operator. Besides, in the other two NV scenarios we observe a lower percentage of traffic offload, i.e. up to 20% decrease at the home operator and up to 28% increase at the host operator. The NV-Offload scenario also introduce the same improvements as those observed in the NV-RSRQ for low femtocell densities, while minor difference is observed for higher densities. In fact, these two scenarios employ the same RRS triggering algorithms that results in the same number of triggered RRS requests.
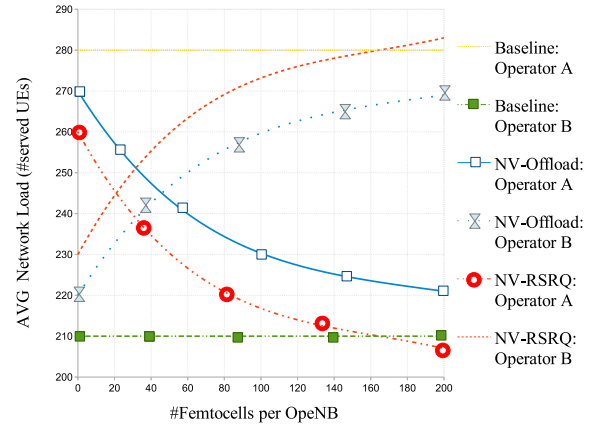
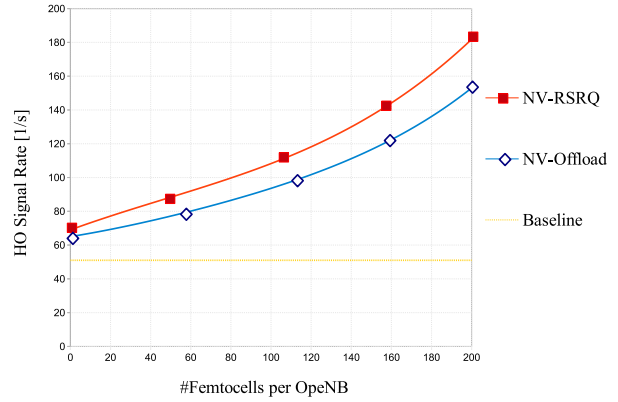The main drawback of the RRS service, however, is the increase in the handover signaling, which is due to the signaling procedure required for establishing the NV-based link [44]. Fig. 15 shows that when the mobile cellular network of Operator B is composed by macro OpeNBs only, i.e. when the number of femtocells per OpeNB is equal to zero, the employment of the proposed RRS service results in a small increase in the handover signaling rate for the UEs registered in Operator A. On the other hand, as the number of femtocells increases (in the host operator), the handover signaling rate (for the UEs registered in Operator A) also increases due to the presence of additional OpeNBs at the host operator.

In short, from the simulation's analysis, we have observed that the proposed RRS service enables operators to achieve a prominent gain of the users' performance at the cost of a slight signaling increase due to the higher number of handovers. Moreover the simulation results have shown that the gain/costs of proposed RRS service are mostly influenced by the triggering phase in the proposed RRS service. Indeed, the algorithms to employ in the triggering phase represent a fundamental parameter to negotiate in the SLAs.

VIII. SUMMARY AND HIGHLIGHTS

In this paper we propose an on-the-fly RRS scheme between different mobile infrastructures so as to provide mobile devices with the freedom to access all available radio resources around them. Such on-the-fly RRS is empowered by employing the concepts of SDN and virtualization of radio access resources. We argue that the RRS service can enable convergence of the available wireless infrastructure around us, and step forwards in achieving the convergence as foreseen by the 5G: convergence of SDN, virtualization, and wireless control, convergence of heterogenous wireless infrastructure, and above all, convergence of different operators' infrastructure in a transparent manner.

We propose two different SDN enforcement approaches depending on the trigger and control of the RRS: device-centric & network-centric. Through extensive simulations, we show how average throughput and delay per user is improved by deploying each of these two approaches. The simulation results also demonstrate better balance of traffic over different wireless radio access. The major drawback of the RSS service, however, is seen as the increase in the rate of the handover signaling. We further elaborate the pros and cons of these two approaches: on the device, we are in the best position to make decision on where to connect to with minimum overhead; on the other hand, since the wireless infrastructure around us belong to different authority, support from the network is required to create necessary links for the connection of devices to other than their home operator's infrastructure. We can summarize that combination of these two approaches can potentially outperform each of the approaches in various scenarios. There are number of open research problems in order to successfully accomplish the proposed resource sharing. Among those, we discuss road ahead in providing the AAA, negotiation of the SLA between operators, new revenue models and spectrum auctioning, fine-grained measurement and control, SDN enforcements, novel admission control, and end-to-end signaling and optimizations.

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