MULTI-TENANT SLICING FOR SPECTRUM MANAGEMENT ON THE ROAD TO 5G

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***Abstract*—The explosive data traffic demand in the context of the 5G revolution has stressed the need for network capacity increase. As the network densification has almost reached its limits, mobile network operators are motivated to share their network infrastructure and the available resources through dynamic spectrum management. Although some initial efforts have been made to this direction by concluding sharing agreements at a coarse granularity (i.e., months or years), the 5G developments require fine timescale agreements, mainly enabled by network slicing. In this article, taking into account the radical changes foreseen for next generation networks, we provide a thorough discussion on the challenges that network slicing brings in the different network parts, while introducing a new entity capable of managing the end-to-end slicing in a coherent manner. In addition, according to the paradigm shift that operators share their resources in a common centralized pool, we design a cooperative game to study the potential cooperation aspects among the participants. The experimental results highlight the performance and financial gains achievable by operators through multi-tenant slicing, providing them with the necessary incentives for network upgrade towards 5G.**

***Index Terms*—DSM, slicing, multi-tenancy, cooperative games, coalitions, sharing, H-CRAN, NFV, SDN.**

INTRODUCTION

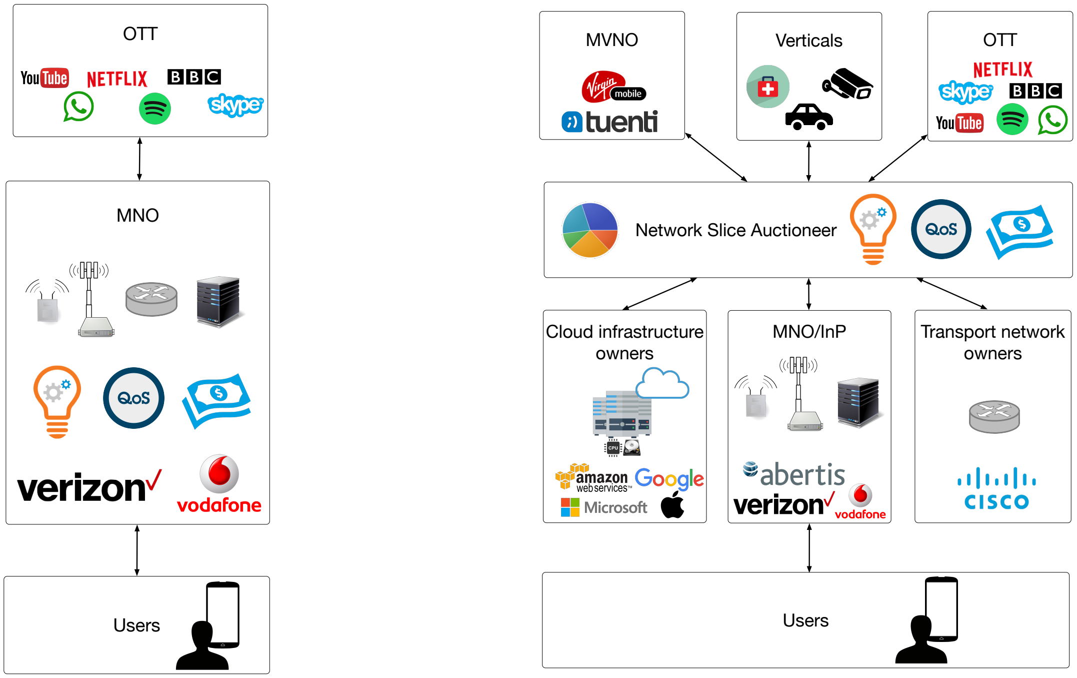
Mobile data traffic explosion is expected to set stringent requirements for 5G mobile networks by the end of 2020. A 1000-fold capacity increase is estimated due to the growing number of smart devices and the widespread diffusion of bandwidth-greedy applications, while sub-millisecond latencies will have to be guaranteed for enabling new delay critical services [1]. A revolutionary upgrade of current networks is needed for providing quality of service (QoS) support to a huge variety of services, while keeping complexity low by designing scalable infrastructure and protocols. However, the cost of such upgrades is prohibitive for most mobile network operators (MNOs), especially since their main return of investment (ROI) is derived from charging end users with relatively low cost flat tariffs. Hence, the traditional business model, where a few big MNOs independently deploy and expand their infrastructure for end-to-end (E2E) service provisioning (Fig. 1a), has already reached its breaking point. To overcome this problem, a new business model, depicted in Fig. 1b, has emerged in the last decade, encouraging the cooperation among MNOs and other market players. Three main sharing interactions can be identified. Firstly, passive and active sharing solutions have been adopted by MNOs, aiming to reduce capital (CAPEX) and operating expenditures (OPEX), respectively. Another sharing opportunity for MNOs is to act as infrastructure providers (InPs) and lease part of their deployed infrastructure to mobile virtual network operators (MVNOs), i.e., MNOs that look for coverage/capacity extension in a given geographical area, or those wishing to enter the service provisioning market without owning a spectrum license or a standalone network deployment. Finally, there is an ongoing discussion on the potential market opportunities stemming from the provision of attractive fee-based on-demand service guarantees by the MNOs towards third party service providers, such as over-the-top (OTT) players (e.g., streaming providers) and vertical industries (e.g., e-health, surveillance, automotive), exploiting the available cloud and communication resources through the E2E infrastructure.

In addition to these sharing interactions, the MNOs are strongly motivated to fully exploit the scarce network and spectrum resources by optimizing the network operation. Thanks to heterogeneous networks (HetNets), improved transmission technologies (e.g., multiple antenna technologies, coordinated multipoint transmission) and enhanced interference management techniques, current systems have already approximated the upper bound of spectrum efficiency regions, whereas communications in the millimeter-wave frequencies is a promising solution for 5G capacity boost. However, a further extension of the available bandwidth can be achieved through the harmonization of the licensed spectrum utilization among different MNOs and technologies, in both time and space domain. Since spectrum reframing would be prohibitively expensive, standardization bodies and manufacturers are currently very active in dynamic spectrum management (DSM) for frequency sharing.

The main efforts related to DSM are dedicated to:

- The extension of LTE-A carrier aggregation principle in the 5 GHz unlicensed spectrum
- The aggregation of different technologies, for instance, LTE and Wi-Fi
- The application of cognitive radio principles, for tiered priority spectrum access [2]
- The implementation of flexible and scalable network sharing solutions

With respect to network sharing, while long term sharing agreements at a coarse granularity (months/years) are being established between MNOs [3], fine-scale sharing mechanisms,



(a) (b)

Figure 1. *Business model with: a) Standalone deployment of E2E infrastructure; b) Heterogeneous ecosystem of sharing partners.*

which will be the core of the 5G architectural revolution, are still under investigation. In particular, the novel paradigm of *network slicing* will drive the optimization of DSM and infrastructure utilization, enabling an evolving ecosystem of heterogeneous players to enter the market, and providing adequate financial incentives to MNOs to upgrade their networks towards 5G.

Taking into account the latest developments in network sharing, we describe the network slicing paradigm and possible use cases, detailing the state of the art (SoA) and the relevant standardization efforts. Then, we propose a novel E2E architecture for DSM through multi-tenant slicing, detailing the necessary infrastructure upgrades and the key technical challenges, along with a new management entity named *network slice auctioneer*, which acts as intermediary among the market players. Finally, we present a specific study case that illustrates the advantages of 5G multi-tenant network slicing for a sustainable evolution towards 5G.

NETWORK SLICING

Current LTE-A systems lack flexibility, having no support for elastic network sharing, which is expected to be the key enabler for a sustainable road to 5G. Network slicing has been recently introduced to provide both fine-scale sharing mechanisms among InPs/MNOs and dynamic QoS provisioning for third parties (i.e., MVNOs, OTTs and verticals), and has already attracted the attention of the main standardization bodies, which foresee dedicated efforts in their future releases. Through this technology, parallel sets of customized resources, that is, the *network slices*, can be dynamically isolated from the pool of network resources, thus enabling the network-as-a-service (NaaS) concept. Through slicing, MNOs can extend coverage and capacity in real time, avoiding the traditional long-term agreements that may not reflect the actual resource requirements of the network. Besides, slices can potentially include heterogeneous resources from the radio access network (RAN) to the cloud infrastructure, therefore, third parties are given the opportunity to dynamically provide their services in a customized manner.

A layered representation of slicing in 5G networks is depicted in Fig. 2. At the bottom, the physical infrastructure is split among isolated slices and is abstracted as:

1. Cloud computing resources, depicting the pool of data centers (DCs) for service development
2. A virtual switch, symbolizing the E2E pool of communication resources (access, core, and transport network) used for service delivering

The LTE-A portion of the network is highlighted in light gray color, with respect to the overall 5G network, and its lack in flexibility and scalability is represented by locking the support for slicing over its infrastructure. Indeed, legacy networks are generally composed of special-purpose hardware, capable of implementing only specific functions. Consequently, computing, storing, and communication resources cannot be flexibly customized, with no or limited support for QoS management. Finally, three well-known use cases for service differentiation through network slicing are displayed:

1. LTE-like telecommunication services for MNOs, MVNOs, and OTTs
2. High capacity video/audio streaming for OTTs
3. Massive Internet-of-things (IoT) for verticals and OTTs

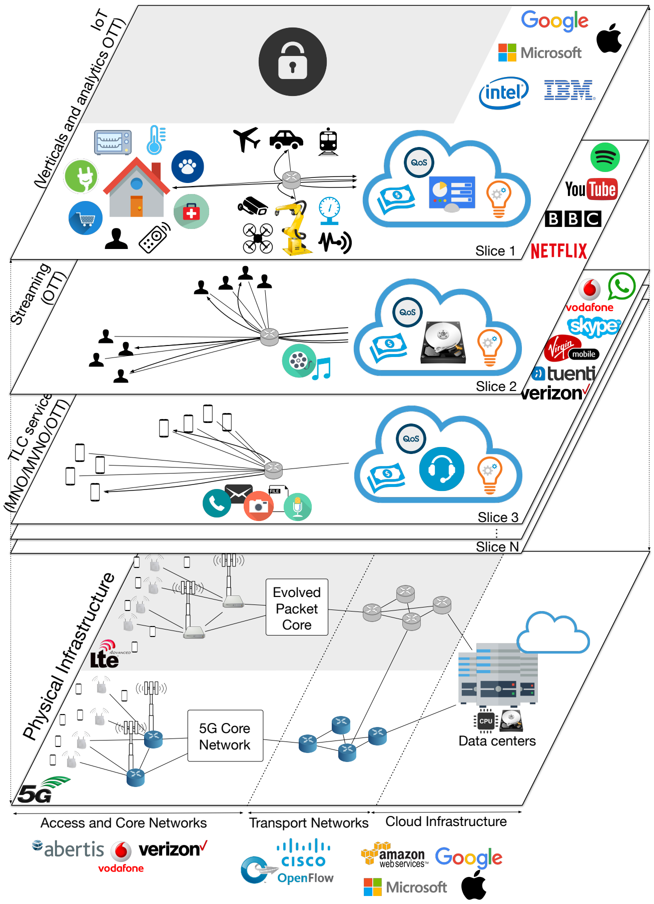


Figure 2. *5G flexible network slicing.*

SoA for Network Sharing and Slicing

Herein, we review the SoA for network sharing and slicing, including both standardization efforts and architectures proposed in the literature for flexible multi-tenant slicing.

3GPP access and core network sharing: An overview of the sharing architecture proposed by 3GPP Release 14 [4] is illustrated in Fig. 3a. The aforementioned architecture allows master operators (MOPs), that is, the InPs, to share their RAN and/or core network (CN) with participating operators (POPs), that is, the MVNOs. MNOs can act as MOP or POP depending on whether they offer or seek coverage/capacity extension. According to the standards, each network element (NE), such as eNodeBs (eNBs), home subscriber server (HSS), serving or packet data network (PDN) gateway (S/P-GW), mobility management entity (MME), and policy and charging rules function (PCRF), is associated with an element manager (EM), possibly colocated with the NEs. The overall network is then handled by a network manager (NM), who, through type 2 interface (Itf-N), provides end-user functions for the management of single NEs or given subnetworks. The NEs are grouped in subnetworks according to vendor, technology or their employment in RAN/CN. Finally, the MOP network manager (MOP-NM) can open RAN/CN management functionalities to the POP network manager (POP-NM) through type 5 interface, with multi-vendor and multi-technology support. Both EMs and MOP-NM shall adopt self-organizing network (SON) functions for the automation of the sharing mechanisms.

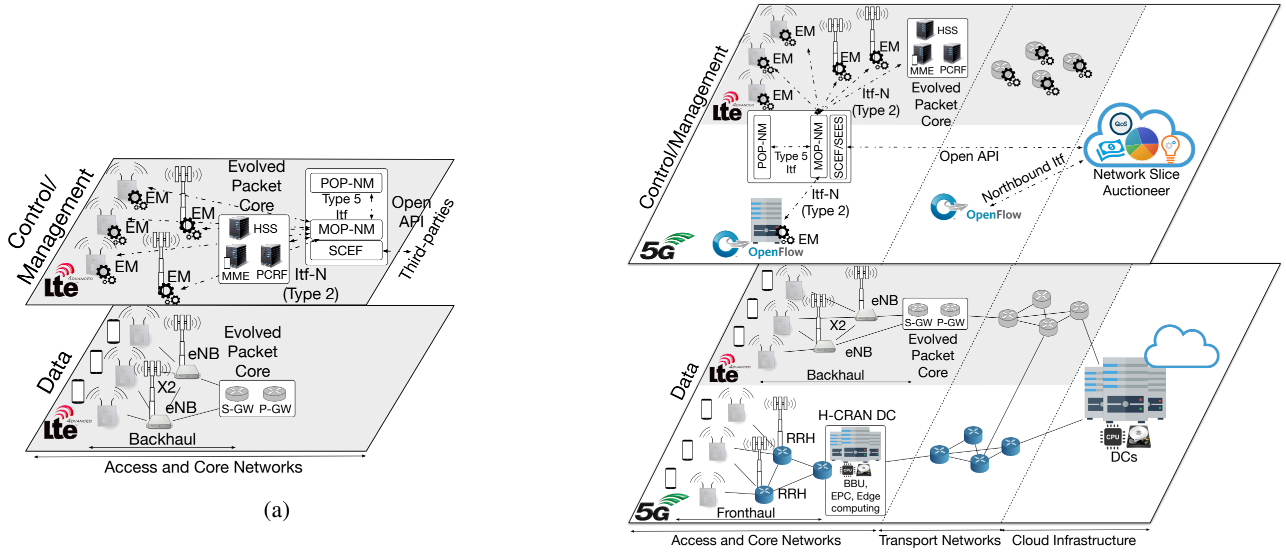
According to RAN sharing requirements for 5G, defined by 3GPP Release 15 [5], a maximum and minimum allocation can be statically reserved to each POP, over a specified period of time and/or region. On the other hand, if unplanned additional capacity is needed by a POP, available spare capacity shall be dynamically allocated. In [6], an on-demand automated capacity brokering study has been proposed in scenarios like periodical capacity excess during night hours, or short-term extra capacity needs during special events (e.g., sports, concerts, fairs). MOP shall optimize network resources while respecting the agreed shares of each POP, and shall be able to perform adequate pricing, by recording the resource usage of each POP compared to the planned one, differentiating between downlink and uplink, and among different QoS profile criteria [4]. Sharing among MOP and POPs is regulated by agreements on legal, financial, technical, and operational aspects, defining shared resources, rights and duties of each operator. These agreements normally stipulate long-term commitments, which represent a limitation, in terms of flexibility, of the current network sharing mechanism, and which we aim to improve through our proposed architecture.

Recent efforts for network slicing: 3GPP foresees support for network programmability by securely opening network services and capabilities to third parties, under service level agreements (SLAs) and with abstraction from underlying network interfaces and protocols. In this regard, the service capability exposure function (SCEF) and the service exposure and enablement support (SEES) have been introduced respectively for LTE-A in Release 14 [7] and for 5G in Release 15 [5]. 3GPP defines the interfaces among SCEF and the RAN/CN entities within the trust domain of the MNO, while those towards the third party OTTs/verticals are application program interfaces (APIs) defined by other standardization bodies. Besides, the SCEF signaling flow for setting up a session with required QoS is described, where the decision is taken by the PCRF. Examples of exposed services to third parties include network access authorization, traffic prioritization, charging policies, and network statistics, among others.

In [5], 3GPP also introduces the concept of dedicated network slices for efficient resource utilization and enhanced third parties user experience. Hence, slices shall be customized according to requirements on functionality (e.g., priority, charging, security), performance (e.g., latency, data rates) or set of served users (e.g., public safety users, corporate customers). The requirements identified by 3GPP for 5G slicing are:

- The on-demand slice creation, allocation, modification, and deletion guaranteeing isolation among each other
- The provision of suitable APIs to third parties for slice monitoring and management
- The elastic adaptation, within minimum and maximum limits, of the slice capacity
- The support for slice prioritization
- Multi-slice/multi-service support for a given user equipment (UE)

However, fine-scale flexible slicing orchestration still remains an open issue, since it is not yet included in the 3GPP specifications. An interesting approach is presented in [8], where a *5G slice broker* colocated with the MOP-NM and



(a)

(b)

Figure 3. *Sharing architectures: a) Standard network sharing architecture; b) Enhanced network sharing architecture for E2E network slicing.*

the SCEF/SEES is defined. This broker provides management capabilities to third parties (through the Itf-N interface) and handles SLA negotiations through SCEF/SEES. The necessary interface enhancements for automated slicing management are also presented in [8], as well as a two-layer resource allocation strategy, in which the pool of resources is first split into different slices, and then intra-slice resource optimization takes place, according to the specific policy of the slice tenant.

Furthermore, only RAN/CN network slicing has been addressed up to this moment, as illustrated in Fig. 3a, while E2E slicing mechanisms are required for providing full QoS support. Therefore, below, we propose an enhanced architecture for flexible full network sharing through fine-scale E2E multi-tenant slicing.

ENHANCED NETWORK SHARING ARCHITECTURE

Herein, we propose an enhanced network sharing architecture, which enables E2E multi-tenant slicing. First, we briefly review the technological innovations required at the data plane for making network slicing a reality, then we define the enhanced control/management entities for flexible E2E network slicing, and, finally, we introduce the slice auctioneer, for E2E slicing bargaining and QoS support. The proposed architecture is compared with the SoA for highlighting the importance of network flexibility at all layers in order to enable E2E slicing support. In Fig. 3b, data and control/management planes of legacy and 5G networks are illustrated (in grey light and white, respectively), where the network infrastructure is divided in three segments: access and core network, transport network, and cloud infrastructure.

Data plane virtualization: With regard to the data plane (at the bottom of Fig. 3b), we show how, in our vision, the 5G infrastructure would evolve by employing the most promising SoA technologies for network virtualization. Heterogeneous cloud RAN (H-CRAN) architecture replaces eNBs with software defined remote radio heads (RRHs) in charge of analog radio frequency functions, while the baseband units (BBUs) in charge of digital baseband functionalities are centralized and deployed as virtual instances in a commercial-off-the-shelf (COTS) small-scale DC [9]. H-CRAN centralized architecture enables fast and enhanced network optimization (e.g., coordinated transmission functionalities, interference management, and energy efficiency) with considerable CAPEX/OPEX reduction [10]. The local DCs are connected among themselves and to the set of available RRHs through a possibly software defined wired/wireless fronthaul, which substitutes the legacy backhaul.

The same DC will be exploited for implementing RAN/CN functionalities and, when possible, for supporting the *edge computing* paradigm. The aforementioned elastic utilization of H-CRAN resources is enabled by the network function virtualization (NFV) paradigm [11], which improves scalability by virtualizing and decomposing logical network functions into a set of interoperating subfunctions, that is, the virtual network functions (VNFs), which can be migrated and instantiated in different COTS platforms. Like fronthaul and backhaul, the legacy transport PDNs, generally created out of special-purpose and vendor-specific hardware, are substituted with programmable software defined networks (SDNs) [12], which interconnect different geographical areas and offer access to the cloud DCs. All these enhancements improve network flexibility and enable enhanced QoS provision, with significant impact on the value chain.

Control/Management plane programmability: The top of Fig. 3b shows the significant enhancement of the control/management plane achievable by deploying programmable networks. Thanks to the H-CRAN architecture, multiple standalone RAN/CN EMs can be centralized and possibly colocated with the MOP-NM, to which they are interconnected through software defined logical interfaces. In addition, the virtualization paradigm enables the flexible orchestration of the control/management entities in the form of VNFs, in

Orchestrator	Responsibilities	Multi-tenant slicing related challenges
SON EM/MOP-NM	• Network self-configuration • Self-optimization • Self-healing	• Automated setup of shared RAN/CN (e.g., cell identity, neighbor cell discovery, and base station configuration) • Joint dynamic optimization of network resources (e.g., coordinated transmission, interference management, virtual BBU optimization at the DC) • Automated network backup through redundant pooled infrastructure
SCES/SEES	• SLA negotiation intermediary • Network functionalities exposure	Security support through: • Slice isolation for third parties protection • Functionality access authorization for MNOs/InPs safeguard
5G slice broker	• Flexible RAN/CN slicing according to SLAs • Two level slicing: – High priority to 3GPP functionalities – Extra resources for third parties • VNFs allocation and mobility management	Guarantee of 3GPP time constraints (e.g., hybrid automatic repeat request) and service level sub-millisecond E2E delays through: • Cooperative distributed computing among multiple H-CRAN DCs • Dynamic VNFs migration among DCs, for instance: – VNFs with strict time requirements close to where they are required – VNFs with high interconnectivity demands colocated in the same DC • Dynamic management of the RRH/BBU split of functionalities, depending on the fronthaul technology and the real-time support for COTS platforms
SDN controller	Dynamic slicing of fronthaul, backhaul, and transport PDNs	VNFs interconnection according to: • Slice topology • Service requirements
5G slice auctioneer	Dynamic real-time E2E slice bargaining: • Performance optimization • Cost reduction	Joint dynamic planning and negotiation of network VNFs, for instance: • Boost of delay tolerant RAN/CN functionalities by adding extra VNFs at the cloud infrastructure • Delay critical services can be moved to the H-CRAN DC • VNFs can be possibly shared among more NEs for cost minimization

Table 1. *5G architecture orchestrators and challenges for flexible sharing and QoS provision.*

such a way that prompt control/management operations can be performed by appropriately migrating the correspondent VNFs. For instance, VNFs with strict time requirements can be instantiated close to where they are required, and multiple VNFs with high interconnectivity demands can be colocated in the same DC.

In the proposed architecture, MOP-NM, SCEF/SEES, and slice broker are colocated, as in [8], since this approach offers enormous architectural advantages. More specifically, the slice broker can easily negotiate SLA requests and expose network control capabilities to third party providers through the SCEF/SEES interfaces, as well as it can gain direct access to the RAN/CN monitoring and configuration through the MNO-MN. Moreover, encouraged by the network virtualization technologies proposed for the 5G infrastructure enhancement, we suggest the integration in software of the standardized MOP-NM, the SCEF/SEES, and the 5G slice broker for faster slice negotiations and management. The automated allocation of network resources through the described slicing architecture enables the appropriate programmability degree needed for flexible network adaptation to different services with variable requirements. Moreover, on-demand slice orchestration is expected to take place at a fine timescale[1], in such a way that resource usage is optimized with small granularity and all third parties can get NaaS opportunities.

Apart from the great benefits for the third parties, the integration of MOP-NM management functions with 5G slicing orchestration enables a new paradigm for flexible multi-tenancy among MNOs/InPs and MVNOs. Indeed, the current long-term contractual mechanisms for RAN/CN sharing could be substituted by automated real-time slicing, where MVNOs without network infrastructure can reduce CAPEX/OPEX by avoiding the deployment of the POP-NM and negotiate slices as general third party service providers. Likewise, multiple MNOs seeking coverage/capacity extension can pool their networks into a joint-venture InP [4], exploiting slicing orchestration for real-time flexible DSM and infrastructure sharing. MNOs' shares could be translated into a minimum reserved slice allocation, while on-demand additional capacity can be provided through dynamic slice adjustment. This new paradigm represents a great opportunity in terms of both:

1. Cost reduction thanks to infrastructure simplification
2. Flexibility improvement thanks to fine-scale slicing, while at the same time operators could maintain the required control over the underlying network

Besides, it is coherent with the business model evolution according to the economy of scale concept, where a few big market players specialize themselves in the acquisition of infrastructure and spectrum (i.e., InP)[2], in order to rent capacity to the rest of the stakeholders, who focus on service provisioning (i.e., third parties).

As far as fronthaul, backhaul, and transport networks are concerned, SDN architecture adds scalability and programmability thanks to the available open standard controllers (e.g., OpenFlow), which enable flexible VNF migration and management. Indeed, the SDN controller could be integrated with the MOP-NM for flexible interconnection among VNFs, such as the dynamic mapping of virtual RRHs and BBUs over the fronthaul. Furthermore, similarly to SCEF/SEES, the SDN controller provides third parties with dynamic network management support, by allowing them to flexibly program the control plane through an open interface (the northbound interface). Therefore, third parties can define network slices through the SDN controller, by isolating the required bandwidth

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[1] Current technology allows slice orchestration at a subminute timescale.

[2] For instance, the Spanish operator Telefónica has announced the creation of a subsidiary company for the management of its infrastructure on a global scale, aiming at improving the ROI through the third party service provision. https://www.telefonica.com/es/web/press-office/-/telefonica-creates-telxius-a-global-telecommunications-infrastructure-company.

on the network links and by properly configuring the forwarding tables in the switches and routers [13]. Besides, the proposed architecture introduces further enhancements in terms of CAPEX/OPEX reduction. In particular, according to Fig. 3b, multiple controllers placed at the forwarding devices' locations are substituted with a central open standard SDN controller for scalable network configuration. Nevertheless, the network programmability features provided by the independent adoption of a slice broker for the RAN/CN, and an SDN controller for the fronthaul, backhaul, and transport networks, are not sufficient to ensure full E2E QoS support. Towards that goal, we propose our vision, where we introduce an auctioneer for E2E slicing orchestration, which will be explained below.

E2E network slice auctioneer: Albeit network management and QoS prioritization mechanisms are already supported for legacy RAN/CN and transport networks, they are limited to their respective network segments according to proprietary policies, which leave third parties with limited or no control over the network optimization strategies. In the current market ecosystem, third parties set more stringent requirements over underlying networks and, consequently, they demand a more active role in E2E network customization.

According to the proposed architecture, third parties can negotiate network slices by direct communication with the 5G slicing broker for RAN/CN slicing and with the SDN controller for the transport network slicing. On the other hand, a unique framework for the automated orchestration of E2E network slices might be sought by third parties, especially those that are interested in a high-level monitoring and control of the network, and willing to leave the resource optimization to the network owner, under the constraint of respecting the agreed SLAs. To this end, we introduce a novel entity in the management plane, named *E2E Network slice auctioneer*, which is placed at the cloud, behaves as intermediary between the network owners and the third parties, and performs the following duties:

- Receiving third parties service requirements
- Bargaining SLAs with both InPs/MNOs and transport network owners on behalf of the competing third parties, for the allocation of appropriate E2E network slices
- Monitoring the allocated slices through open APIs and trading for dynamic adaptation to variable requirements
- Managing billing according to the SLAs and charging additional tariffs to third parties for its intermediation
- Releasing the network slices when the third party service provision ends

In Table 1, we summarize the main management entities introduced in the proposed architecture for flexible network slicing, providing both responsibilities and challenges. Most of the challenges are related with the joint respect of RAN/CN temporal requirements and third party service requirements, when network virtualization technologies are employed. Indeed, although sub-millisecond service latencies have been already demonstrated by industrial testbeds, standardization bodies are still working on this topic. For instance, 3GPP targets in the future releases the shortening of the hardware processing time and the provision of reduced transmission time intervals. Furthermore, [14] proposes H-CRAN architecture and protocol modifications, for enabling further latency reductions.

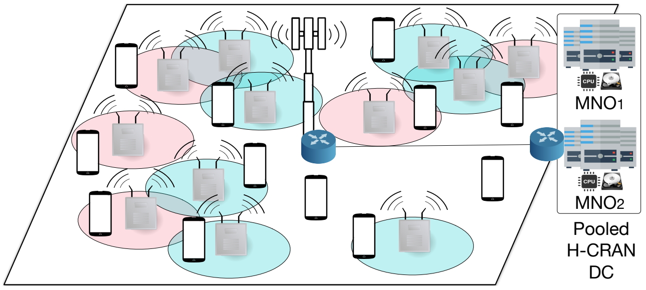


Figure 4. *System model for multi-tenancy incentives: coexisting MNOs with pooled spectrum and infrastructure.*

Below, we propose the financial incentives for MNOs to adopt this novel sharing scheme.

INCENTIVES STUDY CASE FOR MULTI-TENANT SLICING

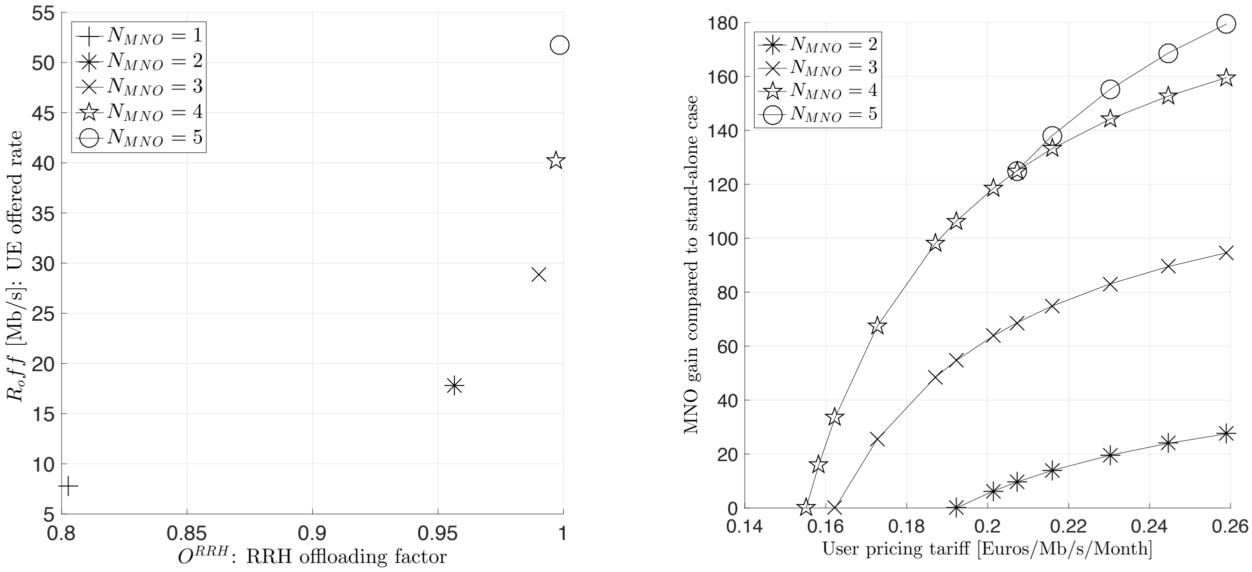
Herein, we investigate the incentives provided by flexible joint DSM and network sharing, where a set of coexisting MNOs decide to form a joint-venture InP and share the whole infrastructure through multi-tenant slicing. More specifically, we employ coalitional game theory to model the MNOs cooperation and evaluate the potential margin for profit and performance gains.

System model: We consider a set of N operators, coexisting in a given area, and owning:

- A specific portion of the total subscribers in that area (i.e., the market share)
- Spectrum license
- The proposed virtualized infrastructure and enhanced architecture, where H-CRAN, NFV, and SDN are exploited for E2E network slicing

An example of this setup (depicting only two MNOs for simplicity) is shown in Fig. 4. We assume that all H-CRAN resources are deployed in the same DC and that the RRHs bandwidth is pooled through carrier aggregation. All network resources of the joint MNO infrastructure are handled by the centralized network manager, who is responsible for UE association, dynamic resource allocation, performance optimization, and power consumption reduction. This setup facilitates the optimal operation of the pooled small cells, enabling significant energy-efficient operations, while it remains transparent to the UE. In particular, in this study, we evaluate the advantages provided by the joint fine-scale switching-off of the pooled resources, which is not allowed by the current coarse granularity sharing agreements.

Coalitional game theory: In the proposed cooperative game, the MNOs face the decision of whether to deploy their 5G networks independently, or to create a coalition by pooling the resources as described above. Specifically, we seek the conditions under which the coalition formation is beneficial for the MNOs and identify when the grand coalition formed by all coexisting MNOs is the most convenient option. We adopt the MNO profit (i.e., the difference between the revenues from the subscribed users and the H-CRAN OPEX) as the payoff function. In particular, a flat rate price in euros per megabit per second is charged to UEs for a guaranteed data rate, whereas the individual MNO cost is calculated as a portion of the total cost, accounting for the joint H-CRAN power consumption.



(a)

(b)

Figure 5. *Multi-tenancy performance results: a) Coverage and QoS improvement by RAN sharing; b) Profit gain through flexible slicing.*

Performance evaluation and results: The performance evaluation is based on a custom Matlab simulator, where each of the N coexisting MNOs owns a licensed bandwidth of 20 MHz, and holds an equal market share over a pool of 20,000 UEs in an area of 4 Km^2. The number of small cells deployed by each MNO is constrained by a minimum guaranteed downlink data rate of 0.78 Mb/s and by a minimum UE offloading factor of 80 percent from the macro cell to the small cell layer. The H-CRAN power consumption has been modeled based on iJoin project specifications[3]. Results are provided for $N = 5$, although similar outcomes can be verified for higher values.

Figure 5a shows the average offered data rate, plotted over the percentage of UEs associated with the small cells layer (i.e., the offloading factor $\mathcal{O}^{\text{RRH}}_{min}$). It can be observed that joint DSM of the pooled spectrum enhances the coverage of the small cell network, with the offloading factor approaching one when N increases. Additionally, offered rates increase, when bigger coalitions of cooperating MNOs are formed. The results confirm the expected benefits from infrastructure pooling, since UEs can be provided with better coverage and QoS, thanks to a more efficient spatial utilization of the frequency resource.

Figure 5b depicts the MNO profit gain, with respect to a baseline non-cooperative scenario, vs. the UE tariff, for different coalition sizes. The first outcome of Fig. 5b is that coalitions with a higher number of MNOs normally achieve higher gains due to better offered rates. On the other hand, a minimum tariff is required, explained by the fact that, for smaller tariffs, the revenue increase is not sufficient for paying back the additional coalitions costs, when compared with the standalone case. Indeed, by forming bigger coalitions, RRHs operate over a bigger aggregated bandwidth, while more processing power is needed at the BBUs. In this context, flexible multi-tenant network slicing offers significant opportunities for OPEX reduction and limits the cost increase in larger coalitions. More specifically, the fine-scale joint optimization of the BBU resources can take advantage of the statistical multiplexing gain, achievable when traffic distribution varies dynamically in time and space domain [15]. Lastly, the minimum tariff depends on the coalition's size, determining whether forming some coalitions could be always beneficial, or only under given conditions. For instance, in Fig. 5b, subcoalitions (i.e., up to $N = 4$) formed by a higher number of coexisting MNOs are always preferable to smaller ones, as a lower minimum tariff is required and higher gains are provided. Different is the case of the grand coalition (i.e., for $N = 5$), which provides the highest gain only when minimum tariff is charged. This is explained by the fact that, when comparing the grand coalition with the subcoalition of four MNOs, the statistical multiplexing gain is not sufficient for limiting the cost increase, thus a higher minimum tariff has to be set for enabling the gains offered by the grand coalition. In all cases, the incentives are significant and could be certainly extended by including the sharing interactions with third parties.

CONCLUSION

In this article, we shed some light on the challenges that multi-tenant DSM and network slicing bring in the next generation networks, introducing the SoA technologies and architecture, together with new entities that are required for flexible network management. Moreover, taking into account the potential cooperation among coexisting MNOs, we proposed a game theoretic framework to study the performance and financial gains offered through fine-scale infrastructure sharing. The results showed that, as long as the provided conditions are respected, multi-tenancy is beneficial as more operators join their forces, providing them with the necessary incentives for network upgrade towards 5G.

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