RESOURCE SHARING IN HETEROGENEOUS CLOUD RADIO ACCESS NETWORKS

MARCELO ANTONIO MAROTTA, NICHOLAS KAMINSKI, ISMAEL GOMEZ–MIGUELEZ,
LISANDRO ZAMBENEDETTI GRANVILLE, JUERGEN ROCHOL, LUIZ DASILVA,
AND CRISTIANO BONATO BOTH

ABSTRACT

Heterogeneous cloud radio access networks incorporate the heterogeneous network and cloud radio access network concepts for next generation cellular networks. H-CRANs exploit the heterogeneity of macro and small cells from HetNets, enabling cellular networks to achieve higher spectral efficiency. Meanwhile, concepts from C-RANs involving baseband units and remote radio heads enable H-CRANs to insert a centralized point of processing for cellular networks, reducing capital and operational expenditures. In this article, we investigate resource sharing in H-CRANs at three levels: spectrum, infrastructure, and network. For each level, we discuss the benefits and challenges, highlighting key enabling technologies that make resource sharing feasible in H-CRANs, such as software defined radio, virtualization, network function virtualization, and software defined networking. Through these technologies, H-CRANs can be virtualized in an overlay network capable of achieving enhanced infrastructure and spectrum sharing.

INTRODUCTION

In this article, we examine the *sharing opportunities* enabled by the new heterogeneous cloud radio access networks (H-CRANs) [1] at the spectrum, infrastructure, and network levels. H-CRANs enable these opportunities through the integration of heterogeneous networks (Het-Nets) and cloud radio access networks (C-RANs).

From HetNets, H-CRANs inherit the tiered deployment of small and macro cells. Small cells, such as picocells (low power traditional base stations) and femtocells (small area access points, often placed indoors), increase spectrum reuse, resulting in significant gains in network capacity. C-RANs introduce digital functional units, called baseband processing units (BBUs), to handle computing workloads, such as signal processing and resource management. Moreover, C-RAN also inserts radio functional units, called remote radio heads (RRHs), to handle RF translation [2]. Within the BBU, a centralized processing entity called a central processor computes workloads while accounting for quality of service (QoS) requirements (e.g., low round-trip time and high bandwidth) as well as resource constraints (e.g., power, time, and frequency bands). Centralizing processing enables optimized orchestration of the number of users per base station, energy consumption, and interference [3].

The H-CRAN was conceived to go a step further in performance by incorporating cloud computing into HetNets to accomplish large-scale cooperative signal processing and network functionalities with increased network capacity [4]. Such large-scale cooperative signal processing enables H-CRANs to exploit advanced spatial signal processing techniques in the physical layer (PHY), such as centralized massive multiple-input multiple-output (MIMO) and distributed large-scale spatial cooperative processing [1]. Meanwhile, the cloudification of network functionalities enables H-CRANs to perform cooperative radio resource management (CRRM) [5] and cooperative self-organizing networking (CSON) [3] to schedule and reorganize resources to supply the huge bit rate demand for ultra-dense communication scenarios.

Integrating two separate network architectures is not challenge-free [4]. The multi-tiered approach of HetNets increases the complexity of interference avoidance [3]. Separation of functionality into RRHs and BBUs, as suggested by C-RANs, incurs the need for a higher-capacity backhaul to avoid delays and service degradation [6]. Fortunately, many of these challenges are offset by the dynamic resource sharing enabled by H-CRANs.

We discuss such resource sharing in H-CRANs considering three levels: spectrum, infrastructure, and network [7]. In terms of spectrum sharing, H-CRANs facilitate improved spectral efficiency through distributed multi-antenna use, intertier interference mitigation, and dynamic spectrum access. At the infrastructure level, physical entities (e.g., antennas,

Marcelo Antonio Marotta, Lisandro Zambenedetti Granville, and Juergen Rochol are with the Federal University of Rio Grande do Sul.

Nicholas Kaminski, Ismael Gomez-Miguelez, and Luiz DaSilva are with Trinity College Dublin.

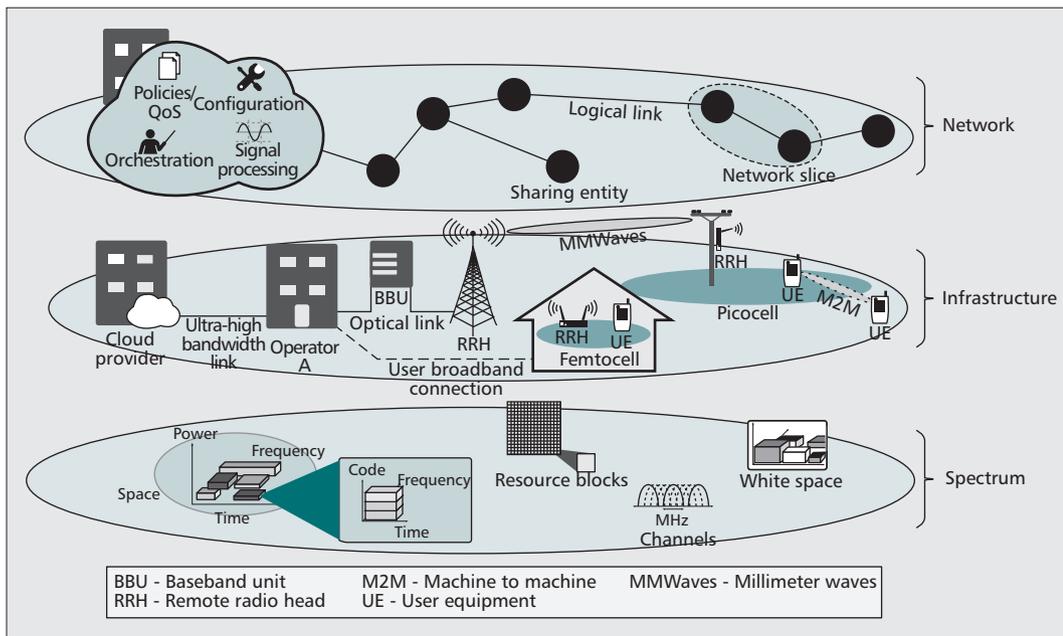Cristiano Bonato Both is with the Federal University of Health Sciences of Porto Alegre.

Figure 1. H-CRAN: resource sharing levels.

Through virtualization in H-CRAN, concepts from HetNet and C-RAN begin to blur, because femto-cells and picocells are created by RRHs instead of low power base stations and access points.

This means that the infrastructure workload is computed at the BBU, where resource availability as well as overloading of physical entities becomes easier to assess.

base stations, backhaul, and access points) can be shared among network operators. At the network level, spectrum and infrastructure from an H-CRAN can be abstracted into network slices defined by higher-level metrics (e.g., throughput and processing). At each of these levels, an H-CRAN enables resource sharing benefits including a dynamic pool of spectral resources, enhanced infrastructure coverage, and virtual networks tailored to particular service goals [8].

The advantages of resource sharing in the context of H-CRANs are significant, although research on this topic is in its early days. We advance the state of this research through the:

- Systematic investigation of resource sharing in H-CRAN, exploring three levels: spectrum, infrastructure, and network
- Identification of major challenges in employing dynamic resource sharing in H-CRAN
- Outlining of research directions to address the major challenges of resource sharing in H-CRAN
- A summary of trending technologies for resource sharing in H-CRAN
- An experiment to measure the gains of spectral efficiency in H-CRAN through resource sharing

All of our contributions intend to exploit resource sharing in H-CRANs, investigating the feasibility, opportunities, and challenges, as well as quantifying the benefits of using it in H-CRANs.

The remainder of this article is organized as follows. In the next section, we outline three views of resource sharing in the context of H-CRANs, based on spectrum, infrastructure, and network sharing. We then address each of these in more detail in subsequent sections. After, we present results of a preliminary quantitative analysis of the benefits of resource sharing and H-CRANs. Finally, we present our conclusions and directions for future work.

CONCEPTS OF RESOURCE SHARING IN H-CRANS

In this section, we present an overview of resource sharing in H-CRANs. To present this overview, we divided an H-CRAN into three sharing levels, depicted in Fig. 1.

Spectrum sharing: The radio frequency spectrum is a costly and finite resource bounded by licenses and agreements. Therefore, sharing spectrum among operators becomes an option to extend the pool of available resources [9]. Spectrum sharing may be performed through different allocation units (e.g., channels used on IEEE 802.11 and resource blocks from Long Term Evolution [LTE] frames). In addition, unused portions of the spectrum called white spaces can also be used as allocation units to be shared through dynamic spectrum access. Each allocation unit can be expressed as power, frequency, time, space, and code, being shared and computed at the BBU.

Infrastructure sharing: With the increasing traffic from mobile devices, operators have to constantly upgrade their radios access and backhaul infrastructure, incurring additional capital expenditures (CAPEX) and operational expenditures (OPEX) [10]. Sharing infrastructure among operators presents a promising solution to reduce costs. Nowadays, a key factor for achieving infrastructure sharing is the virtualization of physical entities by decoupling their functionality from the hardware through a standardized software programmable layer [7]. Through virtualization in H-CRANs, concepts from HetNets and C-RANs begin to blur, because femtocells and picocells are created by RRHs instead of low-power base stations and access points. This means that the infrastructure workload is computed at the BBU, where resource availability as well as overloading of physical entities becomes easier to assess.
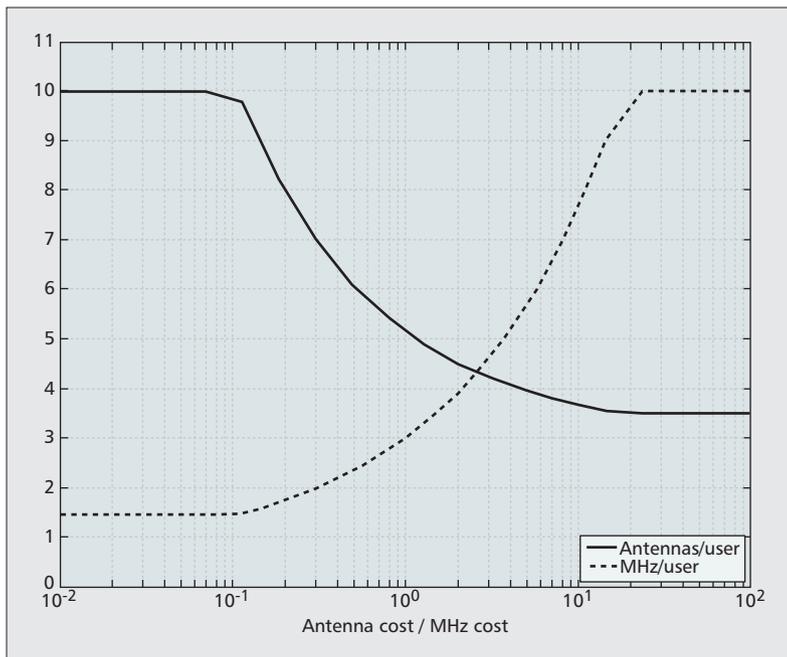
Network sharing: Resources of spectrum and

Figure 2. Optimum number of antennas and spectrum per user.

infrastructure can be abstracted into sharing entities, network slices, and logical links. A sharing entity represents a set of available resources (e.g., a base station, a set of interconnected base stations, or part of a base station, such as antennas). Network slices, in turn, are the arrangement of available resources among two or more sharing entities.

Furthermore, logical links are sharing entities of a link type that connect others. Given this abstraction, network sharing focuses on managing available resources, regardless of their physical representations (e.g., spectrum and infrastructure). At this level, the BBU can be responsible for processing all the network configuration, orchestration, signal processing, and accounting for policies/QoS requirements.

Resource sharing has been extensively investigated in terms of spectrum sharing [9, 11], infrastructure sharing [7, 10], and network sharing [12, 13]. In such investigations, research focused on topics such as resource scheduling, fairness, reliability, flexibility, elasticity, energy efficiency, CAPEX and OPEX minimization, and interference management. In this article, we focus on the promise and challenges of resource sharing in the context of H-CRANs.

SPECTRUM SHARING

Combining the centralized computation of C-RANs with the multi-tiered architecture of HetNets presents several opportunities for sharing at the spectrum level. First, this combination simplifies the interference and orchestration processing problems encountered by both approaches. Second, secondary use of spectrum — in a licensed shared access (LSA) mode — becomes feasible with the capabilities of H-CRANs. Each of these opportunities is described below.

HetNets are already regarded as an effective method of achieving higher spectral efficiency, as evidenced by Third Generation Partnership Project (3GPP) Releases 10, 11, and beyond. The main reason for this endorsement is the opportunity for reuse of spectrum at several different network tiers. However, enhanced intercell interference coordination (eICIC) is necessary to deal with interference among network tiers sharing the same spectrum. eICIC reduces interference in the frequency domain by employing carrier aggregation (CA), in the time domain with almost blank subframes (ABS), or by using power control [14]. Enabling advanced frequency and time domain techniques in traditional network architectures requires a high degree of base station connectivity in the form of a direct X2 interface between pico and macrocells.

H-CRANs, different from HetNets, directly enable the application of advanced CA and ABS techniques because processing for both pico and macrocells is orchestrated from the same BBU. Moreover, the central processing aspects of C-RANs, combined with the multi-tier architecture of HetNets, enable new methods to handle inter-tier interference [1]. Such an application of interference cancellation, based on the differing power levels among tiers, is discussed in a non-cooperative sense by Learned *et al.* [11]. The centralized nature of an H-CRAN architecture furthers this approach by easing the identification of suitable channels for co-channel inter-tier operation.

The centralized processing provided by the integration of HetNets with C-RANs enables the application of new methods for efficient spectrum use. Eliminating the processing constraint of backhaul by computing base stations' workloads with zero delay at BBUs paves the way for ideal backhaul interference coordination. Cloud-computing-based coordinated multipoint (CC-CoMP) provides an example of such coordinated transmission and reception. A CC-CoMP-enabled H-CRAN resembles a large distributed MIMO system where femto, pico, and macrocells are simply RRHs connected to a centralized baseband processing center in which signals are jointly processed. By eliminating the strict backhaul and synchronization requirements among distributed cells, joint processing becomes practical and economically viable in H-CRANs.

When using CC-CoMP, user rate increases with the number of picocells or antennas involved, even in the case of single-antenna UE. This improvement suggests a trade-off between the number of cooperating cells and spectrum [2]. The impact of the increasing number of picocells and antennas is clearer when considering a virtual network operator obtaining antennas and spectrum from a pool, and configuring the network on the fly. The pool of antennas is a feature of H-CRANs, whereas the spectrum pool may come from LSA, for example. The network operator becomes free to use spectral and infrastructure resources according to the leasing cost of each and required performance. In Fig. 2, the trade-off is depicted through the optimal number of antennas and spectrum (megahertz) required to satisfy a minimum rate constraint of 60 MB/s and signal-to-interference-plus-noise ratio (SINR) of 10 dB as a function of the ratio of the antenna to spectrum costs. The study in Gomez-Miguelez *et al.* [2] outlines scenarios for

which more infrastructure and less bandwidth use is better and vice versa. The inherent flexibility enabled by H-CRANs supports the dynamic trade-off between infrastructure and spectrum.

The flexibility of the H-CRAN also enables future infrastructure services that go beyond infrastructure as a service. H-CRANs allow the spectrum to be shared at a much finer granularity than alternative approaches. In LTE, for example, sharing can occur in a resource block or in a subframe, whereas the joint processing enabled by H-CRANs allows sharing at the level of symbols. Finer granularity of sharing enables better adaptation to different operator demands and network heterogeneities, resulting in improved resource utilization. Furthermore, we can also consider spatially multiplexed streams belonging to different operators and sharing the same spectrum, that is, confining the signals from different operators to different physical locations while using the same spectrum. In this scenario, an H-CRAN performs signal processing to convert the different streams into a single real signal that will be transmitted through the air, as shown in Fig. 3. These operations may be similar to today's orthogonal frequency-division multiplexing (OFDM) or filter bank multicarrier (FBMC) modulation and spatial precoding. Each operator's stream of complex samples is modulated and encoded differently, offering vendor variety or service/market/client adaptation, but operating in the same spectrum bands.

Finally, H-CRAN architectures enable the application of cognitive radio techniques for spectrum sharing. An H-CRAN can be viewed as a large-scale, highly capable cognitive radio, where several distributed radios are connected to a central processing element. The H-CRAN processing unit has a clear picture of spectrum use from its numerous distributed sensor elements, allowing high confidence when selecting channels. The integration of such a volume of sensing data directly enables the realization of LSA-style use of spectrum by providing sufficiently reliable information to respect the spectrum rights of a primary user.

At BBUs, central decision making entities, with access to a wealth of information, require less complex techniques for the determination of intelligent actions. Since these techniques are centrally administrated, regulation of autonomous radio action is simplified; that is, regulators need only monitor the decisions of one central element, rather than several distributed ones. More than any other aspect, easing the requirements on effective regulation makes H-CRAN architectures an enabling technology for the use of cognitive radio methods for spectrum sharing.

INFRASTRUCTURE SHARING

According to 3GPP, infrastructure sharing among network operators is classified in two categories: passive sharing and active sharing [15]. In the former, operators share their network related entities that are not computational, such as sites, building premises, and masts [7]. For example, in some Brazilian cities, the deployment of new towers in some areas is only grant-
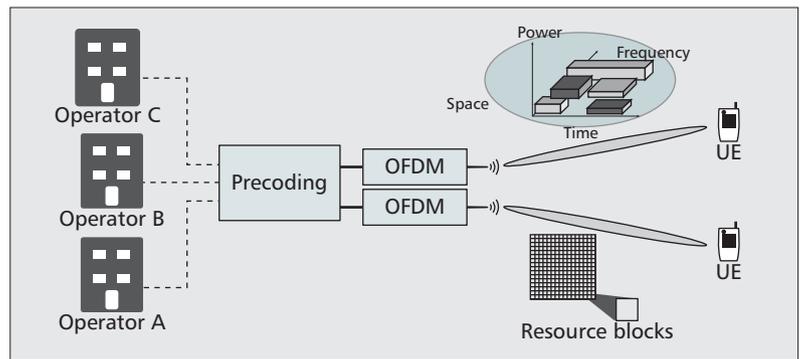

Figure 3. H-CRAN: spectrum sharing level.

ed when the capacity of all towers in these areas is exhausted. Therefore, in this case, passive sharing among operators is mandatory to provide capacity without the need for new towers. Active sharing, in turn, encompasses entities that are directly bound to network processing (e.g., base stations, access points, backhaul, routers, and switches). Mechanisms that abstract these entities can be used to make them accessible from software, easing their remote management through the network [10]. Such an abstraction can be performed, for example, through the use of virtualization and software-defined networking (SDN) paradigms. Since passive sharing is well exploited and is already provided by third parties [10], in this article we focus on active sharing, which enables massive reduction of CAPEX and OPEX.

In H-CRANs, different from HetNets and C-RANs, RRHs replace base stations and access points, among other radio access network (RAN) devices, as depicted in Fig. 4. Through a high-capacity backhaul based on millimeter-waves and/or optical links, RRHs upload their workload (e.g., modulation and MIMO processing) to be computed at the BBU. Different from a C-RAN environment, focused on macrocell workloads, in H-CRANs the huge amount of processing workload coming from macro and small cells will eventually make the sharing of BBUs a need, creating BBU pools. Operator resources from macro and small cells can be efficiently shared by having their workload optimally processed at shared BBU pools through cloud-computing-based cooperative radio resource management (CC-CRRM) [1]. For example, by centralizing the workloads, the BBU pool can easily identify a macrocell as overloaded, directing users to hand over to a shared underutilized small cell from another operator (e.g., using IEEE 802.21) without the need for additional steps to process the inter-operator handover.

In a recent 3GPP technical report [15], different scenarios of infrastructure sharing are defined for common cellular networks. We have remapped these scenarios to the H-CRAN context. Next, for each remapped scenario, we present a brief description and discuss a major open challenge.

In the first scenario, the core of an operator is shared with other operators to handle two or more RANs. In H-CRANs, the sharing of an operator core can be represented by the BBU
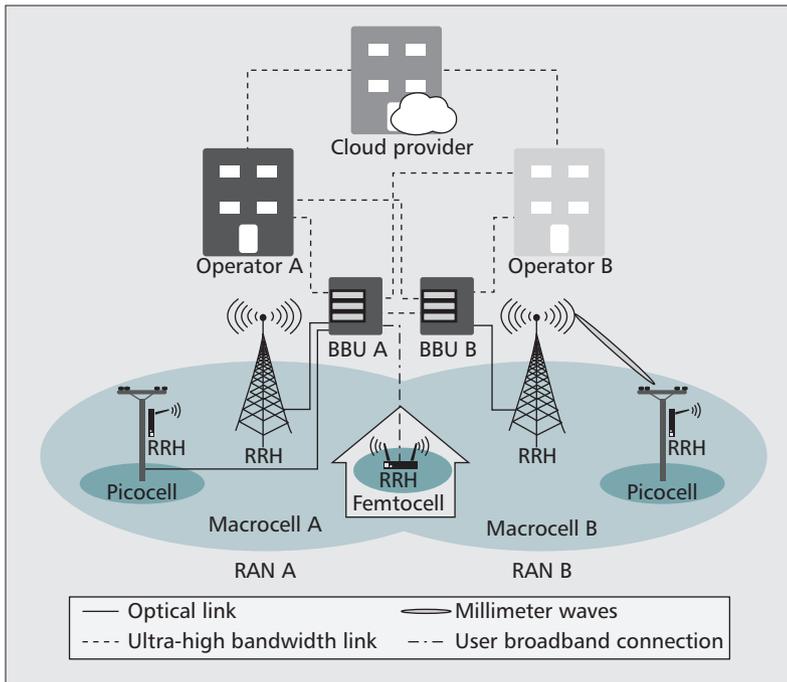
Figure 4. H-CRAN: infrastructure sharing level.

processing capacity being shared among different RANs. For instance, in Fig. 4, suppose that BBU B becomes overloaded by processing heterogeneous cells workloads from RAN B. Then BBU B can forward its workload to be processed on the idle BBU A. In this scenario, a major challenge is how to share the processing capacity among BBUs by distributing the workload without inserting more complexity. The workload distribution can be modeled as an optimization problem that considers the distribution of workloads among BBUs, similar to, for example, a bin packing problem considering frequency, time, and space, and the container as the BBU. It means that the workload distribution is an NP-hard problem that must be processed without compromising BBUs to meet strict performance requirements. For example, according to a white paper from China Mobile Institute Research [5], BBUs have a time restriction for processing workloads of 5 μs for 8 antennas using 10~20 MHz per carrier in LTE/LTE-Advanced (LTE-A). According to the strict performance requirements, heuristic solutions must be explored to solve the problem of workload distribution.

In the second scenario, a RAN from an operator is shared with other operators without mixing spectrum resources. In H-CRANs, the same scenario would be represented by BBUs processing workloads from a RAN without mixing their spectrum resource pool. BBUs may exploit cloud-computing-based cooperative self-organization networking (CC-CSON) techniques to orchestrate all the RANs connected to the BBU pool. Using CC-CSON, the BBUs exchange information to allow subscribers from different operators to use the same RRHs and gain access to the network. However, the isolation of spectrum resources of each operator is kept (i.e., frequencies of both operators are not shared). In Fig. 4, RAN A could have its workload divided

between operator A and operator B to be forwarded and processed by their respective BBUs. This forwarding can be performed directly between BBU A and BBU B, or indirectly through a cloud provider. In this scenario, the main open challenge is how to provide the workload exchange among BBUs. The workload exchange requires the definition of a new interface and stack of protocols among BBUs, whereas there are already interface definitions for communication between BBUs and RRHs, such as the common public radio interface (CPRI) and open BBU-RRH interface (OBRI) [5].

The third and fourth scenarios refer to the sharing of coverage area among operators performed partially and fully, respectively. Partial sharing means that RANs from different operators can be shared within a small geographic area. Full sharing, in turn, combines RANs from different operators completely to enlarge their coverage in a country. BBUs could accept access from subscribers of different operators inside their own infrastructure to expand the coverage area. In addition, BBUs can share their workload, as well as their RANs, with other operators' BBUs, considering all the entities shown in Fig. 4. In this scenario, a partially shared H-CRAN has the challenge to provide a policy mechanism to grant permission to or restrain operators from using other RANs. For fully shared H-CRANs, scalability becomes a major challenge because there are physical limitations to moving workloads among a huge number of BBUs as well as managing them. Moving a workload can be modeled as a shortest path or minimum spanning tree problem, where BBUs represent nodes connected by optical links that represent the edges. The weight of each edge can be measured in terms of a weighted sum that considers the quantity, delay, and processing time needed to process the workload being exchanged. Different solutions can be explored, such as Dijkstra's algorithm for shortest path or Bernard Chazelle soft heap for a spanning tree problem.

Network Sharing

Integrating spectrum and infrastructure that belong to different operators using an H-CRAN requires careful orchestration of resources to preserve bilateral agreements among operators. To this end, the state of the art indicates solutions based on the abstraction of a heterogeneous physical layer to an overlay [7, 10, 12], which is called the network layer (Fig. 5). At the network layer, sharing is performed according to high-level network metrics (e.g., throughput and processing). To achieve such sharing, we highlight four key enabling technologies:

- SDR for RF processing decoupling in a software layer [5]
- Virtualization for PHY complexity abstraction and isolation [7]
- Network function virtualization (NFV) for scalability and network functionalities isolation [10]
- SDN for centralization and improved orchestration of network control and management [13]

Below, for each of these technologies, we provide a brief description as well as a discussion of their employment in H-CRANs and major open challenges.
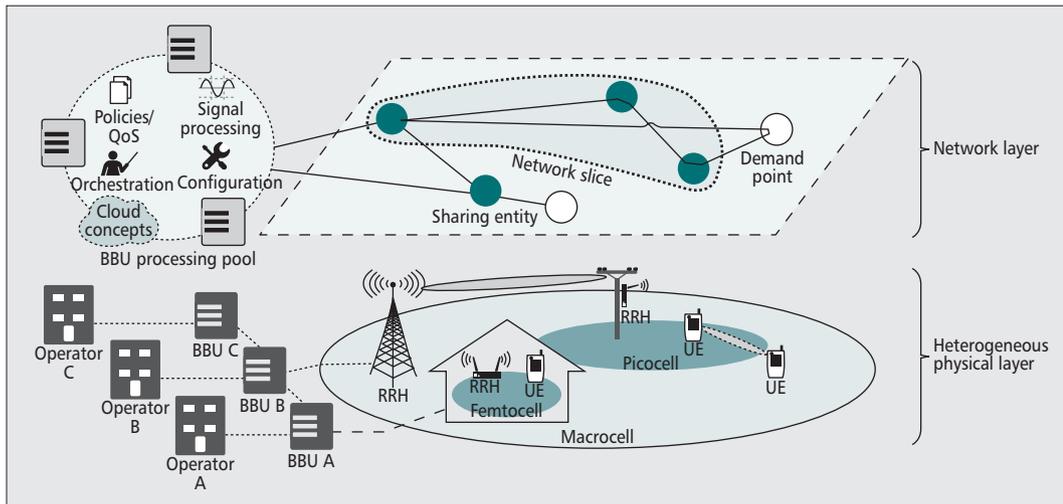
Figure 5. H-CRAN: network sharing level.

SDR refers to technologies where the baseband processing is performed by software modules running digital processors [5]. In H-CRANs, the use of software modules enables the baseband processing by a software layer in BBUs. As a consequence, operations such as coding, modulation, signal processing, and radio parameter configurations can easily be computed by the processing pool. Currently, an open challenge for SDR in H-CRANs is to provide an optimal solution to split radio functionalities between RRHs and BBUs to avoid performance degradation in terms of latency aggregation and higher energy consumption [16].

Virtualization enables network entities to have their heterogeneous physical complexity abstracted to a homogeneous virtual sharing entity. Also, this technology avoids mixing workloads from different operators, isolating resources from the physical network in self contained virtual machines [12]. In H-CRANs, BBUs and RRHs can be virtualized in sharing entities having their physical resources (e.g., frequencies and backhaul capacity) homogenized in higher network metrics. Sharing entities can be linked, creating an overlay network, also called network layer, as depicted in Fig. 5. Within a network layer, UEs that generate traffic can be represented by demand points. Network slices can then be created to combine resources from sharing entities to meet the requirements of demand points. However, the dynamicity of wireless environments imposes challenges for virtualization in H-CRANs, because virtualization must be performed over a dynamic resource pool that must be frequently recalculated to guarantee the correct operation of sharing entities [7].

NFV encapsulates network functionalities into software packages that can be distributed through the network to be performed in a homogeneous environment (e.g., a virtualized network) [13]. In H-CRANs, NFV provides scalability for sharing among operators that involves a huge number of BBUs and RRHs, creating large network domains [5]. NFV also provides isolation of network functionalities by creating packages that have execution life cycles completely independent of others. The definition

of a standard platform to manage the life cycles of packages is an open challenge for the realization of NFV in H-CRANs.

SDN has been proposed as a solution for improved orchestration of networks [13]. This orchestration is achieved through centralized controllers that provide a clear separation between control and data planes. In H-CRANs, the controller can be maintained at BBU processing pools. Data flows are established as rules to be deployed in sharing entities, providing rescaling of available resources without compromising the network [12]. A major challenge to realizing SDN in H-CRANs is the creation of an SDN interface that supports wireless network operations such as controlling handover and managing mobility across heterogeneous RANs.

H-CRAN RESOURCE SHARING ANALYSIS

In this section, we summarize the trending technologies in H-CRAN and present the simulation results for spectrum and infrastructure sharing considering an H-CRAN environment.

TRENDING TECHNOLOGIES

We highlight some trending technologies that will be indispensable for conceiving resource sharing in H-CRANs. In Table 1, we classify each technology according to the H-CRAN level and its application. In addition, different shareable resources are also presented as well as the pros and cons for each technology.

Considering Table 1, we can relate each technology of different levels in the concept of resource sharing in H-CRANs. One of the major features of H-CRANs is their capability to reconfigure themselves at each level. Through CC-CRRM, H-CRANs have the potential to exploit the shared pool of spectrum using different techniques, such as frequency-division duplex (FDD), time-division duplex (TDD), and bidding. In addition, combining CC-CRRM and SDR can enable H-CRAN to change its way of accessing shared frequency bands (i.e., DSA or LSA), adapting itself to different operators' policies of spectrum access. Moreover, using CC-CSON, the infrastructure of H-CRANs can become self-

managed, which, combined with virtualization, enables the integration of multi-operator infrastructures under an abstracted shared entity. For each shared entity, NFV technology can quickly distribute network services and functionalities to be executed and supply different operators' subscribers. Finally, SDN can help in the network flows orchestration to improve the performance of shared entities intercommunication, achieving QoS and improved user experience.

SIMULATION RESULTS

We claim that resource sharing is fundamental for achieving higher spectral efficiency in H-CRAN environments. To quantify the resulting efficiency gains (in bits per second per Hertz), we designed two experimental H-CRAN scenarios. For both scenarios, we placed a macrocell in the middle of a 1 km^2 area, representing one sector of a cellular network. UEs are spread randomly in this area. In addition, inside the same area, small cells are randomly placed varying in number [50, 100, 250, 500]. For the macrocell (m), we calculated the mean spectral efficiency (M) according to distances of the UE to the RRH (D). This calculation was done based on a single-input single-output operational mode of a base station from 3GPP LTE-A.

$$\begin{cases} D_m \ < \ 300 \ \text{m} & M_m \ = \ 3.7 \ \text{b/s/Hz} \\ 300 \ \text{m} \leq D_m \leq 600 \ \text{m} & M_m \ = \ 1.875 \ \text{b/s/Hz} \\ 600 \ \text{m} < D_m < 1000 \ \text{m} & M_m \ = \ 0.9375 \ \text{b/s/Hz} \end{cases}$$

For the small cell (s) the calculation was based on the draft of IEEE 802.11 ac 3.0. Each small cell was designed to support 20 UEs, and the macrocell has no support limit.

Trending technology	Level	Resource sharing	Pros	Cons
FDD, LTE-FDD	Spectrum level	• Frequency bands pool	• Symmetric data traffic • Free from interference	• Asymmetric data traffic • No reconfigurable link capacity • High cost • Need of guard band
TDD, LTE-TDD	Spectrum level	• Time slot	• Asymmetric data traffic • No need of paired spectrum • Reuse of frequencies • Reconfigurable capacity	• Symmetric traffic • Inter-tier interference • Complex processing • Synchronization with UEs
Bidding [17]	Spectrum level	• Time slot • Frequency bands • Resource blocks	• Priority insertion	• Need an auction system
Dynamic spectrum access	Spectrum level	• White space	• Unused frequency bands • Cognition • Sharing functionality	• Complex radio functions • Intermittent use • Restrict bands
Licensed shared access	Spectrum level	• Frequency bands	• Sub-leasing • Unused frequency	• Secondary use • Primary UE priority • Spectrum broker
CC-CRRM	Spectrum level	• Frequency bands • Time slot • Space	• Cooperatively management • Interference estimations • Radio resources recalculation • Optimal objectives	• Insertion of delays • Higher complexity used/ shared • Need BBU pool
CC-CSON	Infrastructure level	• BBU • RRH	• Self-configuration • Self-healing • Self-control • Autonomic management	• Insertion of delays • High complexity • Need BBU pool • Need handover technologies
Virtualization	Infrastructure level	• BBU • RRH	• Abstracted level • High level network metrics • Resource flexibility	• Insertion of delays • Hard to guarantee QoS • High complexity
Network function virtualization	Network level	• Network functionalities	• Software bundle • Scalability • Interchangeability of network service	• Hard to manage • Need for orchestrator
Software-defined networking	Network level	• Network flows	• Control/data flow separation • Centralized flow control • Reconfigurable network • Ease the network manage-	• No support wireless substrate • No accounting for wireless conditions

Table 1. H-CRAN trending technologies.

$$\begin{cases} D_s < 50 \text{ m} & M_s = 9.75 \text{ b/s/Hz} \\ 50 \text{ m} \leq D_s \leq 75 \text{ m} & M_s = 4.875 \text{ b/s/Hz} \\ 75 \text{ m} < D_s < 100 \text{ m} & M_s = 2.4375 \text{ b/s/Hz} \end{cases}$$

We also considered that UEs will always try to connect to the RRH with the best received signal strength indicator (usually the closest one). The results of more than 1000 repetitions of Monte Carlo simulations are depicted in Fig. 6.

In the first H-CRAN scenario, we investigated the maximum spectral efficiency reached by deploying small cells without resource sharing, depicted in Fig. 6a. As a baseline, we measured the average spectral efficiency reached by a solo macrocell of 2.134 b/s/Hz, which remains constant because we did not limit the macrocell capacity. By deploying 50 small cells, the average spectral efficiency grows, reaching 5.235 b/s/Hz on average; nevertheless, as soon as the number of UEs per square kilometer exceeds 1000, the efficiency degrades significantly, down to 2.423 b/s/Hz. With the deployment of 250 to 500 small cells, the average spectral efficiency almost reaches the maximum of 9.75 b/s/Hz, but both efficiencies degrade in the presence of 1000 or more UEs.

In the same scenario, to better understand why the spectral efficiency degrades for densities larger than 1000 UE/km², we measured the percentage of saturated small cells, that is, small cells that cannot provide communication to any additional UEs, shown in Fig. 6b. The number of saturated small cells grows quickly between UE densities of 10 and 1000/km². The average spectral efficiency decreases in proportion to the number of saturated small cells. Therefore, a massive number of small cells is required to reach better average spectral efficiency in some densely populated areas. In this case, exploiting the sharing of small cells becomes inevitable.

The second scenario was created to assess the benefits of resource sharing in an H-CRAN environment. From the first scenario, let us assume a density of 10,000 UE/km² with 50 small cells deployed, and average spectrum efficiency of 2.434 b/s/Hz, which notionally represents the infrastructure of an operator that leases infrastructure (receiver) from another (donor). According to LSA methodology [2], shared cells must prioritize the communications of UEs that belong to the donor (i.e., primary UEs) rather than UEs from the receiver. In addition, we must consider that the donor leased both spectrum and infrastructure resources, allowing its BBUs to exchange and process the receiver workload freely through CC-CRRM and CC-CSON [1]. Finally, we measured the spectral efficiency gain of the receiver operator according to the number of shared small cells in use, as shown in Fig. 6c.

By exploiting 100 shared small cells, the receiver may reach the spectral efficiency of 3.87 b/s/Hz for its 10,000 UEs with a low primary UE density (less than 1000 UE/km²). When the receiver uses 250 shared small cells, its 10,000 UEs reach 5.8 b/s/Hz, more than double the spectral efficiency without sharing. Using 500
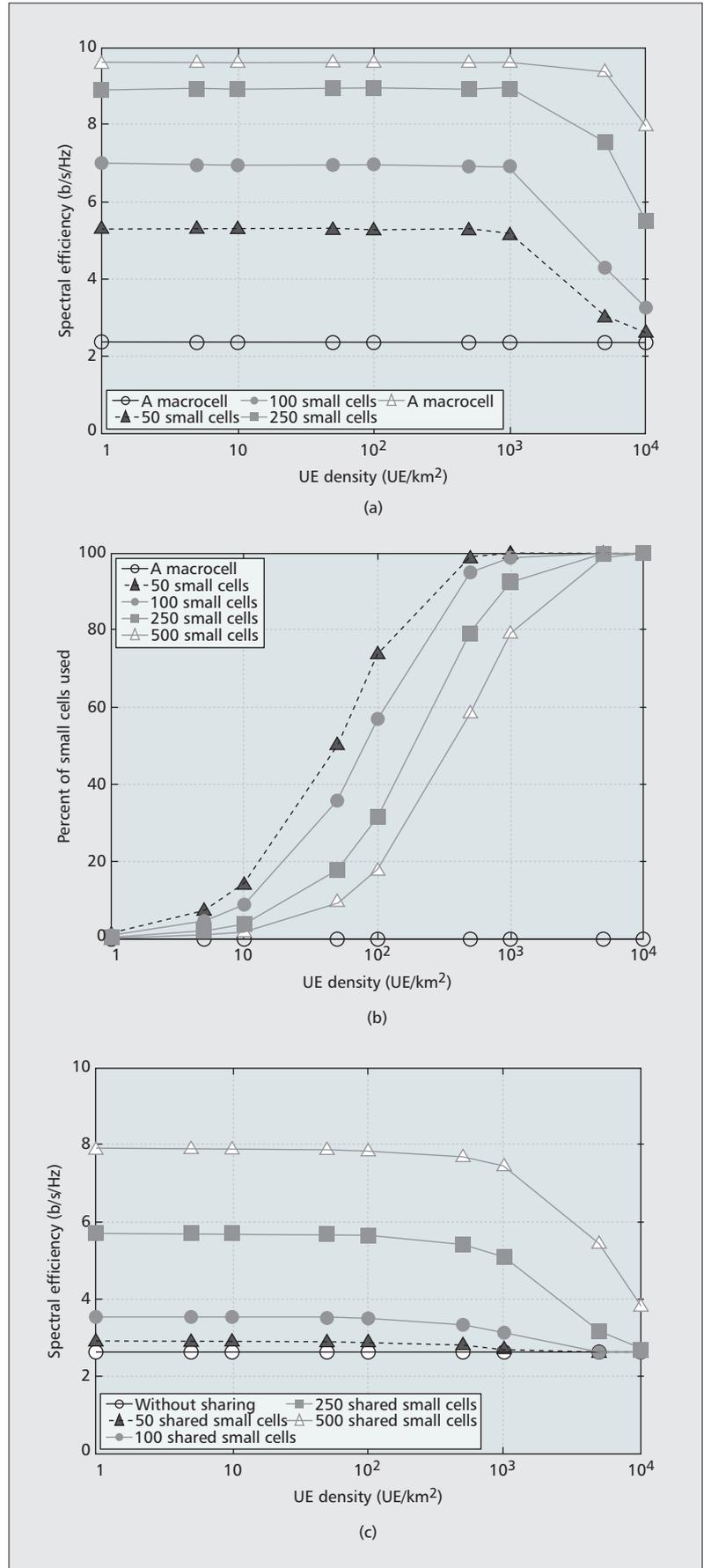

Figure 6. Spectral efficiency and cell saturation for spectrum and infrastructure sharing: a) small cells without resource sharing; b) saturation of small cells; c) small cells with resource sharing.

We have discussed the benefits and challenges of employing resource sharing in H-CRAN architecture. To address these challenges, we exploited three sharing levels: spectrum, infrastructure, and network.

shared small cells, the receiver's UEs can achieve 7.9 b/s/Hz, more than triple the spectral efficiency without sharing. However, when the density of primary UEs exceeds 1000, the receiver's UE spectral efficiency gradually degrades for all the considered deployments of small cells. This means that the receiver can improve its spectral efficiency by taking advantage of shared resources in areas where primary UEs are not fully dominant. Finally, by taking advantage of resource sharing in H-CRANs, receivers can double or triple their spectral efficiency by leasing small cells.

CONCLUSIONS

In this article, we have discussed the benefits and challenges of employing resource sharing in H-CRAN architecture. To address these challenges, we exploit three sharing levels: spectrum, infrastructure, and network. At the spectrum level, H-CRANs enable spectral efficiency gains through coordination and interference avoidance, and facilitate dynamic spectrum sharing. Meanwhile, at the infrastructure level, we map four sharing scenarios from 3GPP to discuss how H-CRANs can potentially reduce CAPEX and OPEX. At the network level, the integration of SDR, virtualization, NFV, and SDN enables the creation of an overlay network to achieve enhanced sharing and orchestration. Also, we summarize trending technologies for conceiving resource sharing in H-CRANs. Finally, we simulate resource sharing scenarios and measure the gains of spectral efficiency for H-CRANs.

REFERENCES

[1] M. Peng *et al.*, "Heterogeneous Cloud Radio Access Networks: A New Perpective for Enhancing Spectral and Energy Efficiency," *IEEE Wireless Commun.*, Dec. 2014, pp. 126–35.
[2] I. Gomez-Miguelez *et al.*, "Cloud-RAN Platform for LSA in 5G Networks — Tradeoff Within the Infrastructure," *IEEE 6th Int'l. Symp. Commun., Control and Signal Processing*, May 2014, pp. 522–25.
[3] S. Liu *et al.*, "A 25 Gb/s(/km2) Urban Wireless Network Beyond IMT-Advanced," *IEEE Commun. Mag.*, vol. 49, no. 2, Feb. 2011, pp. 122–29.
[4] M. Peng *et al.*, "System Architecture And Key Technologies for 5G Heterogeneous Cloud Radio Access Networks," *IEEE Network*, vol. 29, no. 2, Mar. 2015, pp. 6–14.
[5] China Mobile Research Inst., "C-RAN The Road Towards Green RAN," Oct. 2011, v. 2.5, pp. 1–44.
[6] Y. Zhou and W. Yu, "Optimized Backhaul Compression for Uplink Cloud Radio Access Network," *IEEE JSAC*, vol. 32, no. 6, June 2014, pp. 1295–1307.
[7] C. Liang and R. Yu, "Wireless Network Virtualization: A Survey, Some Research Issues and Challenges," *IEEE Commun. Surveys & Tutorials*, no. c, 2014, p. 1–1.
[8] J. S. Panchal, R. D. Yates, and M. M. Buddhikot, "Mobile Network Resource Sharing Options: Performance Comparisons," *IEEE Trans. Wireless Commun.*, vol. 12, no. 9, Sept. 2013, pp. 4470–82.
[9] M. Matinmikko *et al.*, "Spectrum Sharing Using Licensed Shared Access: The Concept and Its Workflow for LTE-Advanced Networks," *IEEE Wireless Commun.*, vol. 21, no. 2, Apr. 2014, pp. 72–79.
[10] X. Costa-Pérez *et al.*, "Radio Access Network Virtualization for Future Mobile Carrier Networks," *IEEE Commun. Mag.*, vol. 51, no. 7, July 2013, pp. 27–35.
[11] R. Learned, S. Johnston, and N. Kaminski, "Cognitive Coexistence: A Throughput Study of Mud-Enhanced Opportunistic Spectrum Access," *Asilomar Conf. Signals, Systems and Computers*, 2013, Nov 2013.
[12] P. Demestichas *et al.*, "5G on the Horizon: Key Challenges for the Radio-Access Network," *IEEE Vehic. Tech.*, vol. 8, no. 3, Sept. 2013, pp. 47–53.
[13] C. J. Bernardos *et al.*, "An Architecture for Software Defined Wireless Networking," *IEEE Wireless Commun.*, vol. 21, no. 3, June 2014, pp. 52–61.
[14] D. Lopez-Perez *et al.*, "Enhanced Intercell Interference Coordination Challenges in Heterogeneous Networks," *IEEE Wireless Commun.*, vol. 18, no. 3, June 2011, pp. 22–30.
[15] 3GPP Tech. Spec. Group Services and System Aspects, "Service Aspects and Requirements for Network Sharing," Oct. 2014, v. 12.0.0, pp. 1–19.
[16] D. Wubben *et al.*, "Benefits and Impact of Cloud Computing on 5G Signal Processing: Flexible Centralization Through cloud-RAN," *IEEE Signal Proc. Mag.*, vol. 31, no. 6, Nov. 2014, pp. 35–44.
[17] L. Doyle, J. Kibilda, T. K. Forde, and L. Dasilva, "Spectrum without Bounds, Networks without Borders," *Proc. IEEE*, vol. 102, 2014, pp. 351–65.

BIOGRAPHIES

MARCELO A. MAROTTA (mamarotta@inf.ufrgs.br) is a Ph.D. candidate in computer science at the Institute of Informatics (INF) of the Federal University of Rio Grande do Sul (UFRGS), Brazil. He received his M.Sc. degree in 2013 from INF, UFRGS. In addition, he received a B.Sc. in computer science from the Federal University of Itajuba (UNIFEI), Brazil, in 2010. His research involves wireless networks, next generation networks, the Internet of Things, software defined radio, and cognitive radio networks.

NICHOLAS KAMINSKI (kaminskn@tcd.ie) is a research fellow at Trinity College Dublin, Ireland. His research focuses on targeted intelligence to act in harmony with flexible radio systems with application to distributed adaptive networks. He advances radio intelligence through experimentation-based research and is co-principal investigator on several European projects that create and develop experimentation platforms and services for an open infrastructure.

ISMAEL GOMEZ MIGUELEZ (gomezi@tcd.ie) is currently a research fellow at the CONNECT Centre at Trinity College Dublin. He received his Ph.D. in telecommunications engineering from Universitat Politecnica de Catalunya, Spain, in 2013. His main research areas of interest are network sharing and network virtualization, software-defined radios, and future network architectures, including distributed multi-antenna systems and cloud-RAN. He has published more than 20 refereed papers in journals and major conferences, and holds one national patent. He is a director of Software Radio Systems Ltd, a spinoff company from CTVR.

LISANDRO Z. GRANVILLE (granville@inf.ufrgs.br) is an associate professor at INF, UFRGS. He received his M.Sc. and Ph.D. degrees, both in computer science, from UFRGS in 1998 and 2001, respectively. He is a member of the Brazilian Internet Committee (CGI.br). He has served as a TPC member for many important events in the area of computer networks (e.g., IM, NOMS, and CNSM) and was TPC Co-Chair of DSOM 2007 and NOMS 2010.

JUERGEN ROCHOL (juergen@inf.ufrgs.br) is an associate professor at INF, UFRGS. He received his M.Sc. degree in physics and his Ph.D. degree in computer science, both from UFRGS, in 1972 and 2001, respectively. His research interests include wireless networks, next generation networks, optical networks, and traffic control on broadband computer networks.

LUIZ A. DASILVA (dasilval@tcd.ie) holds the Chair of Telecommunications at Trinity College Dublin. His research focuses on distributed and adaptive resource management in wireless networks, and in particular wireless resource sharing, dynamic spectrum access, and the application of game theory to wireless networks. He is a co-principal investigator of CONNECT, the Telecommunications Research Centre in Ireland, and an IEEE Communications Society Distinguished Lecturer.

CRISTIANO B. BOTH (cbboth@ufcspa.edu.br) is an associate professor at the Federal University of Health Sciences of Porto Alegre (UFCSPA), Brazil. He holds a postdoctoral title in computer science at INF, UFRGS. He received a Ph.D. degree from UFRGS in 2011 and his M.Sc. degree in computer science from the Ponthifical Catholic University of Rio Grande do Sul, Brazil, in 2003. His research interests include wireless networks, next generation networks, and software-defined networking.