

# An Architecture to offer Cloud-Based Radio Access Network as a Service

Lucio Studer Ferreira<sup>1</sup>, Dominique Pichon<sup>2</sup>, Atoosa Hatefi<sup>2</sup>, Andre Gomes<sup>3</sup>, Desislava Dimitrova<sup>4</sup>, Torsten Braun<sup>4</sup>, Georgios Karagiannis<sup>5</sup>, Morteza Karimzadeh<sup>5</sup>, Monica Branco<sup>1</sup>, Luis M. Correia<sup>1</sup>

<sup>1</sup>: INOV-INESC | IST University of Lisbon, Portugal, {lucio.ferreira; monica.branco; luis.correia}@inov.pt

<sup>2</sup>: Orange, France, {dominique.pichon; atoosa.hatefi}@orange.com

<sup>3</sup>: OneSource, Lda. | University of Coimbra, Portugal, gomes@onesource.pt

<sup>4</sup>: University of Bern, Switzerland, dimitrova@iam.unibe.ch

<sup>5</sup>: University of Twente, The Netherlands {g.karagiannis; m.karimzadeh}@utwente.nl

**Abstract** — This paper addresses the novel notion of offering a radio access network as a service. Its components may be instantiated on general purpose platforms with pooled resources (both radio and hardware ones) dimensioned on-demand, elastically and following the pay-per-use principle. A novel architecture is proposed that supports this concept. The architecture’s success is in its modularity, well-defined functional elements and clean separation between operational and control functions. By moving much processing traditionally located in hardware for computation in the cloud, it allows the optimisation of hardware utilization and reduction of deployment and operation costs. It enables operators to upgrade their network as well as quickly deploy and adapt resources to demand. Also, new players may easily enter the market, permitting a virtual network operator to provide connectivity to its users.

**Keywords** — Architecture; Cloud; RAN; X as a Service.

## I. INTRODUCTION

Seamless wireless communication has become an elementary building block of modern society. Still, to satisfy connectivity and traffic requirements, mobile operators are facing big changes. The worldwide deployment of Radio Access Networks (RANs) is following the progress of Radio Access Technologies (RATs), having evolved from GSM and UMTS to LTE and LTE-Advanced systems [1]. The explosive increase of capacity needs requires dense deployments of Base Stations (BSs) at high CAPEX and Operational Expenditure costs (CAPEX and OPEX) for mobile operators. Of these costs, up to 80% of CAPEX and 60% of OPEX is spent on the RAN [2]. Moreover, while traffic is increasing exponentially (100 times every 10 years [3]), the average revenue per user is decreasing. To support increase of traffic, operators dimension BSs for peak loads, while in reality the offered traffic varies drastically, both geographically and temporally. In fact, measurements report that 50% of sites generate 10% of revenue, while 20% of the BSs carry 50% of the traffic [4]. In terms of network infrastructures, fibre cabling is already a reality in many urban areas, where 90% of sites are connected via fibre to central offices within 10 km [5].

In parallel to these changes in RANs, the cloud computing paradigm [6] is evolving rapidly, where computation, storage and networking resources are offered “as a service”, pooled and provided on-demand, elastically and following the pay-per-use principle. Extending it, the Network Function Virtualisation (NFV) concept [7] aims at running network

functional elements on virtualised computing environments. The Mobile Cloud Networking (MCN) project [8] addresses this challenge, extending the cloud computing paradigm to communication networks, leading to more efficient exploitation of resources, as depicted in Fig. 1. Data Centres (DCs) with General Purpose Platforms (GPPs) can be located at central offices, supporting software-based core and RAN components, its deployment and management being done “as a service”.

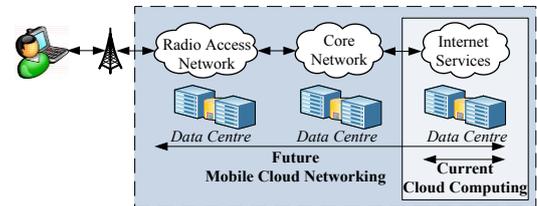


Figure 1. Mobile cloud networking vision.

The objective of the current paper is to propose a novel architecture to offer RAN as a Service (RANaaS), tackling a set of challenges and requirements which due to their complexity are discussed in detail later sections. RANaaS empowers the instantiation of software-based RAN components on GPPs located in DCs. Resources, i.e., computation, storage and networking, are pooled and provided on-demand and elastically, following the cloud computing paradigm, for the adequate performance of the software-based network functional elements. This resulting virtualised RAN can be dynamically operated, maintained and integrated with other parts of the mobile communication system. It enables mobile operators, formally referred to as Enterprise End Users (EEUs), to create new business models and scenarios in the provision of wireless services to Individual End Users (IEUs). With RANaaS, EEUs will be able to quickly deploy and make upgrades to the RAN, instantiating and scaling resources on-demand where and when they are required, and releasing them when not needed anymore. RANaaS will also let new players, like mobile virtual network operators, enter the market to offer services according to specific Service Level Agreements (SLAs), while sharing a common infrastructure.

This paper is structured as follows. Section II addresses the background of RANaaS. Challenges are presented in Section III, while Section IV describes requirements for the RANaaS architecture. In Section V the RANaaS architecture is presented, while in Section VI conclusions are drawn.

## II. BACKGROUND

The RANaaS concept has a background in the Cloud-RAN (C-RAN), NFV and mobile cloud computing concepts. The first building component of RANaaS is C-RAN, a centralised processing, collaborative radio, real-time cloud computing and clean RAN system [9]. Several proposals of architectures for C-RAN exist [9], [10], as well as projects addressing this topic [11], [12]. Many operators, like China Mobile [13], are already conducting trials with centralised architectures to provide fast and dense RAN deployments. C-RAN makes RAN more flexible and efficient, where a BS is split into a Remote Radio Head (RRH) and a Base Band Unit (BBU), linked via an optical fibre front-haul transport network, Fig. 2.

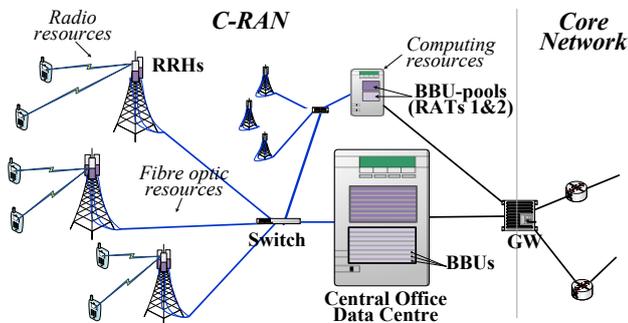


Figure 2. C-RAN architecture.

The RRH is the physical radio part of the BS, composed of the antenna and a small radio unit in charge of radio functions. The BBU aggregates the baseband functions of a BS as well as control and management ones. A BBU is software-based, and can be of any Radio Access Technology (RAT). A BBU can be instantiated on one or multiple Virtual Machines (VM) in a DC. Multiple BBUs, of the same or different technologies, may be grouped in a DC forming a BBU-pool. Such BS split enables one to have cheap and small RRHs in almost infrastructure-less sites, with all the digital processing being elastically supported by cloud-based GPP DCs. The expected impact points up to 15% CAPEX and 50% OPEX savings, compared to distributed 3G BSs, faster system rollout saving up to 1/3 of the time, and saving up to 71% of power compared to a traditional RAN system [2]. Still, currently BBUs run on dedicated hardware platforms. RANaaS extends C-RAN, by taking advantage of GPP platforms, virtualisation and the cloud paradigm, to enable on-demand and elastic allocation of resources to BBUs.

Another building block of RANaaS is NFV, allowing network functions to run over virtualised computing environment. Some motivations include cost efficiency, automated and flexible network operation and faster speed of time to market. The European Telecommunications Standards Institute (ETSI) NFV Group allows the IT and Telecom industries to share their complementary expertise to make NFV a reality. It has recently published several use cases [7], such as the virtualised base station and a framework for operating virtualised networks [14]. RANaaS can be seen as a particular example of NFV, focussing on a virtualised RAN architecture that provides answers to the use of existing cloud computing concepts for the virtualisation of LTE Systems.

A third building block of RANaaS is the cloud computing concept, a movement from a product-based economy to a

service-based economy. Any cloud application should be delivered as a service. Cloud computing is based on a set of principles, such as on-demand and self-service, resource pooling (shared infrastructure), broad access network, rapid elasticity, enabling end-users to easily grow or shrink their cloud computing provisioning based on performance metrics, and a measured service and pay-per-use. RANaaS is innovative by applying the cloud paradigm in its service lifecycle, i.e., the deployment, provisioning, operation and disposal of RAN components.

Similar to RANaaS, the concept of RAN sharing is a user-transparent agreement between operators [15] to avoid network duplication and reduce upfront investment costs. Various types of sharing are possible, such as geographical (national) roaming agreement, passive sharing of in infrastructure (site, tower or antenna) as well as active sharing of RAN and spectrum. RANaaS goes beyond RAN sharing. Based on virtualisation of network components, it enables isolation and an efficient, dynamic, on-demand and elastic usage of resources.

## III. RANaaS CHALLENGES

The main challenge of RANaaS is to enable new business concepts and to allow optimisation of RAN operations by cloud concepts. The introduction of cloud-based network entities requires the design of an appropriate architecture, able to cope with a large range of technological and business requirements. The architecture shall enable a RANaaS provider to offer RAN functions on-demand, automating the deployment and provisioning processes as well as allowing for network scaling during runtime. The architecture shall make it possible to optimise the utilisation of cloud and radio resources, while ensuring that SLAs are met.

To illustrate the RANaaS adoption and introduce some terminology, we present a concrete motivation scenario. A mobile operator EEU has its own LTE core network. Still, it requires RAN access for a given geographical area to serve its customers. The Mobile Cloud Network Service Provider (MCNSP) manages the EEU subscription and appears as provider of integrated services. The EEU gets a services catalogue from the MCNSP and selects a RANaaS jointly provided by RAN Providers (RANPs) A and B. This allows the EEU to connect its customers via RANs from operators A or B to its own core network. The MCNSP acts as an umbrella body that unites several RANPs and supports their interaction, invisible to the EEU, being responsible for end-to-end network connectivity. The EEU may also benefit from support services such as monitoring, load balancing, mobility and bandwidth availability prediction and SLA, which are offered by third parties Support Service Providers (SSPs). RANP fulfils MCNSP's requests by deploying, provisioning, running and disposing RANaaS service instances.

When deploying RANaaS based on the C-RAN architecture, cf. Fig. 2, a set of challenges can be identified. For instance, the fibre optical resources must satisfy very tight requirements in terms of latency, dictating a maximum BBU-RRH fibre length of 15 km [10], and high bit-rate links (a tri-sector site with LTE, UMTS and GSM may require rates of up to 20 Gbit/s [5]). The mapping of RRHs to a serving BBU is another challenge related to load balancing between BBUs or BBU-pools, as discussed in [16]. Thanks to the cloud concept, BBUs can sit in the DC and their resources (processing, storage) can be scaled according to

the load variation of the associated RRHs. However, using GPPs to run BBUs is a challenge because strict timing requirements are present when processing radio frames. These will demand not only a high amount of processing power but also a real time operating system. Also, such applications are not well explored in the cloud domain at the moment, and having BBU software specifically adapted for GPP is a rather complex challenge in terms of code and process optimisation [16]. For load balancing among DCs, BBUs can be migrated from one DC to another, requiring evolved mechanisms to ensure it is done seamlessly for attached end users. A key aspect is the quantification of the relation between load and processing needs at the BBU [16].

RAN sharing, with homogeneous or heterogeneous RATs, is a challenge on its own with the need to ensure service continuity and reasonably fast inter-RAT communication. Equally non-trivial is to ensure support of multi-tenancy, i.e., one RANP supporting multiple EEs, each with specific radio requirements and SLAs. As both radio and computational resources are shared in RANaaS appropriate mechanisms for the integrated management of these resources are needed. Such integrated management needs global view on the current and predicted resource usage.

#### IV. RANAAS REQUIREMENTS

In order to meet the above outlined challenges, the RANaaS architecture should meet several requirements towards the RAN components as well as their integration with other network elements and services.

RANaaS shall be able to allocate resources on-demand and dynamically through load balancing, for the adequate performance of the software-based network functional elements, within one or multiple RATs. Triggers are temporal and geographical variations of load as well as changes in SLA contracts. Appropriate monitoring and prediction mechanisms are needed to provide feedback on geographic and temporal traffic distribution.

Algorithms to support the migration of resources from one BBU to another one are required for efficient management of processing resources. Additional requirements are posed towards the RAN components such as minimised interruption of services in case of failures, guaranteed minimum capacity and maximum delay between network nodes (e.g., BBU-RRH link) and maximum allowed delays within and between DCs.

A requirement specific to multi-tenancy is the need of each mobile operator to administer its radio mobile networks while being isolated from the other operators. In general, RANaaS should allow the mobile operator to have a global operations, administration and management view of its network instance, from the RRH to the BBU, including the front-haul. To support such degree of freedom RANaaS management should include mechanisms (automatic or manual) to dynamically configure and manage any component of the network. The management entity shall be able to configure itself in a self-organised way, providing static/dynamic information on the topology and characteristics of its participants of the RAN.

RANaaS shall allow dynamic sharing of radio resources between multiple cell types (macro, micro, pico ones) of a single or multiple operators in the same or different RATs (e.g. GSM, UMTS, LTE, Wi-Fi), guaranteeing SLAs.

Moreover, the RANaaS architecture should provide end-users connectivity transparently from the used RATs, realising seamless intra- and inter-RAT handovers. This poses strict requirements on the processing and internetworking delays, especially for inter-RAT handovers when SLA-unaware switches may be used. More complex scenarios of simultaneous attachment to multiple RATs additionally set requirements on internetworking for control purposes and service coordination.

#### V. RANAAS REFERENCE ARCHITECTURE MODEL

##### A. Initial Considerations

The RANaaS reference architecture is based on the generic MCN architecture [17]. The RAN service is categorised, according to the MCN architecture, as a primary MCN service. Various Support Services (SSs) provide specific functionalities to RANaaS, such as monitoring, load balancing, mobility and bandwidth availability prediction. Moreover, MCN atomic services such as storage may be used when appropriate. As all services implementing the MCN architecture, the RANaaS Service Instance (SI) is implemented using a number of Service Instance Components (SIC), which are domain specific. The SI is under the control of a Service Manager (SM) and a Service Orchestrator (SO), and uses the facilities of a Cloud Controller (CC). The orchestration of the RANaaS is initiated and managed by its SO. The set of services needed by the RANaaS SI are described in a Service Template Graph (STG).

The proposed RANaaS architecture is depicted in Fig. 3. RANaaS is offered to MCNSPs through the interface of the RANP's SM. Through the MCNSP, a mobile operator (EEU) requests the RANP's SM to create a new RANaaS service instance. The new service instance is then instantiated by the SM and the SO. The SO automatically manages the RANaaS service instance (e.g., making scaling decisions).

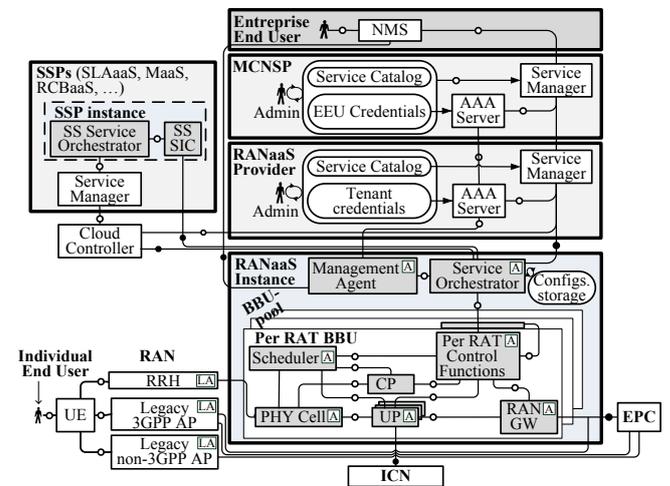


Figure 3. RANaaS reference architecture model.

##### B. Functional Elements

Several functional elements define RANaaS, Fig. 3. The following non-RANaaS specific ones are defined:

- **Service Manager (SM):** as defined in [17], it allows EEUs to request for RANaaS from a MCNSP's catalogue and initiates the RANaaS SI. The SM

provides to the SO relevant information, enabling it to create the SICs.

- **Service Orchestrator (SO):** as for all MCN services [17], it is responsible for the RANaaS SI, from its initialisation to its disposal, including any runtime process, e.g. migration of SIC or auto scaling of VMs to face the current load. In forming the scaling decisions the RANaaS SO uses feedback on (i) the SLA in place, (ii) its own SIC and (iii) monitoring data from supporting services in the RANaaS's STG. The SO can configure SICs, either directly or through the CC. It configures and controls monitoring agents ("A" box in Fig. 3), which feed specific support services (for the sake of clarity of the drawing, the interface is not represented). The SO actively participates in communication with various components: it feeds internal status data to SS SICs, it consumes monitoring data from SS SICs and provides scaling instructions to the CC. Runtime procedures are enabled by interacting with the CC providing a different STG, e.g., for SIC migration.
- **Cloud Controller:** as for all MCN services [17], it triggers the creation of SIs for MCNSPs and supports the management of SICs upon SO instructions.
- **AAA Server:** it contains Authentication, Authorisation and Accounting (AAA) data bases and mechanisms that interact with AAA agents placed at key points in the architecture to deliver centralised AAA.
- **AAA Proxy:** identifies and subsequently provides credentials to the AAA server in charge of the tenant.
- **Subscribers' Credentials:** it contains the subscription credentials related to different service requestors.
- **Management Agent (MA):** in cases where the EEU manages RAN parameters, the MA authenticates and authorises EEU requests that are forwarded to the SO. It can also be used as a place where mechanisms to automatically configure SICs are stored. The management agent is also responsible for configuring legacy agents ("LA" box in Fig. 3), which monitor legacy functional elements.

Next, RANaaS specific functional elements are described. The BS functions are split between RRH (RF transmission) and per-RAT BBU (baseband processing and higher layer functions). The processing part includes layers 1, 2 and 3 (L1, L2 and L3) functions of BSs, corresponding to user and control plane protocol stacks [1]. These are divided into the following functional elements (some proposed in [10]):

- **Phy Cell:** it is responsible for the dynamic multiplexing/demultiplexing of signals into/from frames, for one cell. It is controlled by the scheduler.
- **User Processing (UP):** it corresponds to the dedicated user processing required per user radio bearer in UL and DL. It covers the most processing consuming functions (such as coding/decoding, modulation/demodulation, MIMO processing) that can be migrated to other BBU-pools, in load balancing.
- **Scheduler:** it dynamically controls the access to the shared radio resources according to QoS parameters. It decides on: (1) which IEU to be served during each transmission time interval; (2) which physical resource blocks to be allocated to each IEU; and (3) which modulation and coding scheme to be allocated to each IEU for each transmission. To apply these decisions, the

scheduler has control interfaces with different functional elements. Thus, (1) and (2) lead to the control and management of Phy Cell, and (3) leads to the control of link adaptation function (hosted by the MAC layer in CP and UPs). The scheduler is itself controlled by the radio resource control layer, which is hosted by the Per RAT Control Function.

- **Per RAT Control Function:** it covers all the BS control functions. It is also responsible for the control and configuration of all the layers hosted by CP and UPs, as well as the functionality of the scheduler.
- **Common Processing (CP):** it corresponds to the processing of common control information (independent of IEUs) in UL and DL. It processes the common control channels. The CP is connected to the Phy Cell, and is under the control of the Per RAT Control Functions and the Scheduler. It is also connected via the Per RAT Control Function to external interfaces (those towards external elements such as core network nodes), e.g., S1-MME in case of LTE. The rationale behind the functional splitting between UPs and CP is that the processing effort for common control information is negligible with respect to that for the dedicated UPs, and thus CP would not be migrated.
- **RAN GW:** it is the only functional element seen by the outside world. Its role is to offer security between external elements (e.g. core network nodes and/or EPCaaS SICs) and the RANaaS service instance. It routes downlink packets to the relevant RANaaS functional elements, i.e., UP and Per RAT Control Function. For example, in case of LTE, this is performed by implementing SCTP (for S1-MME) and GTP (for S1-U) relay functions. Design options can be to have the RAN GW inside or outside the BBU.
- **Monitoring Agent (A):** it extracts measures from each MCN primary service ("A box" in Fig. 3) and exposes it – by a regular update, based on triggers or on request – to a logically centralised monitoring system.
- **Legacy Agent (LA):** it enables monitoring of legacy functional elements (e.g., RRH, 3GPP and non-3GPP APs) ("LA" box in Fig. 3). It is managed and controlled by the Management Agent. The interface between LA and SS SIC is not drawn, for the sake of clarity.

### C. External Interfaces

As it can be seen in Fig. 3, there is a complex communication network between the individual components in the RANaaS architecture, managed through multiple interfaces. Internal RAN interfaces are defined by processing procedures and are of lower functional interest. Therefore, we focus on the external interfaces as follows (represented as black bullets in Fig. 3):

- **RAN.SO::SM** – for the communication between the RANaaS's SO and the SM.
- **RAN.SO::CC** – for the communication between the RANaaS's SO and the CC, for the provisioning and on-the-run scaling of the underlying hardware platform.
- **RAN.SO::SS SIC** – it supports the communication the RANaaS's SO and the SS SIC, defining the exchange of data needed for the operation of the SS.
- **RAN.MA::NMS** – it enables both feedback to the EEU on its currently running service and direct management of the RANaaS service instance, if desired.

- **RAN.MA::AAA** – it ensures that the NMS requesting access to the RANaaS instance is authorised to do so.
- **RAN.MA::LA** – it allows the management and performance monitoring of legacy systems by the EEU.
- **RAN.RAN GW::EPC** – it supports the communication to the network core.
- **RAN.UP::ICN** – it supports the usage of Information Centric Networking (ICN) for caching and content migration [18], integrated at the BBU, closer to IEUs.

#### D. Lifecycle

Common to all MCN services [17], the RANaaS lifecycle is split into five stages, which are design, deployment, provisioning, runtime management and disposal. Several design options exist for the RANaaS functional elements implementation, their exact mapping into VMs depending on technical and business conditions. Based on a trigger from a mobile operator (EEU) to the SM, a new instance of a RANaaS SO is created. The RANaaS SO triggers the deployment of all individual SICs making the RANaaS SI available. The parameterisation of the SI corresponds to the needs of the EEU, i.e., the set and coverage of mobile services provided to the IEUs according to specific SLAs. SICs are then customised based on configurations specified by the STG, after that the RANaaS SI is ready to be used.

For example, it is expected that in a business area, IEUs will request high throughputs, which are only satisfied if sufficient radio and processing resources are allocated to the RRHs and associated BBUs, respectively. Subsequently, the runtime management guarantees that components are auto-scaled and migrated by the SO to meet varying traffic demands, reported by monitoring alarms. For example, if due to an event, IEUs' offered traffic increases drastically in a given geographical area, the SO guarantees that adequate computing resources are allocated to support the increased radio request (e.g., RRHs operating with more carriers and larger bandwidths). Once the SM receives a trigger to dispose, the SO and CC will take care of the SICs's disposal, the SO being also then disposed.

## VI. CONCLUSIONS

In this paper an architecture designed within the EU FP7 Mobile Cloud Networking project is presented, which enables the provision of RAN to virtual network operators as service instances based on the cloud-computing paradigm. By making most efficient use of the availability of cloud resources, the architecture allows the operational optimisation of RAN by moving much processing traditionally located in hardware for computation in the cloud. The proposed architecture allows the realisation of several new business paradigms such as multi-tenancy (sharing of radio resources among several operators) and multi-RAT provisioning (service provisioning transparent from the type of RAT used). The architecture's success is in its modularity, well-defined functional elements and clean separation between operational and control functions. In the latter a Service Manager and Service Orchestrator entities play a key role.

Through the architecture design we expect to optimise network aspects such as: hardware utilisation and OPEX decrease (by aggregating resources in a cloud), CAPEX (by offering operators a highly scalable service paradigm), join-in threshold for new operators (via a comprehensive and easy to manage platform) and user satisfaction (via multi-RAT

service provisioning any time anywhere). Whether the performance of the RANaaS architecture meets our expectations will be validated through large-scale experimentation on (radio) network dimensioning, joint management of radio resources and computational load balancing. To support our investigations we are preparing for implementation in with several emulation platforms.

## ACKNOWLEDGMENT

Fruitful discussions and comments from Thijs Metsch, Andy Edmonds and Almerima Jamakovic are acknowledged. The research leading to these results was partially funded by EU's Seventh Framework Programme Mobile Cloud Networking project (FP7-ICT-318109).

## REFERENCES

- [1] H. Holma and A. Toskala, *LTE for UMTS: Evolution to LTE-Advanced*, John Wiley, West Sussex, UK, 2011.
- [2] C. Chen, "C-RAN: the Road Towards Green Radio Access Network", in *Proc. of ICST Workshop on C-RAN*, Kunming, China, Aug. 2012.
- [3] P. Jauhainen, "Energy efficiency in communication networks in Horizon 2020 perspective", in *Proc. Of 24th Tyrrhenian International Workshop on Digital Communications*, Genoa, Italy, Sep. 2013.
- [4] H. Guan, T. Kolding and P. Merz, "Discovery of Cloud-RAN", in *Proc. of NSN Cloud-RAN Workshop*, Beijing, China, Apr. 2010.
- [5] A. Pizzinat, P. Chanclou, "C-RAN architecture and fronthaul challenges", in *Proc. of LTE World Summit*, Amsterdam, The Netherlands, June 2013.
- [6] R. Buyya, J. Broberg and A. Goscinski, *Cloud Computing: Principles and Paradigms*, John Wiley, New York, NY, USA, 2011.
- [7] ETSI, *Network Functions Virtualisation (NFV): Use Cases*, ETSI GS NFV 001 V1.1.1, Sophia Antipolis, France, Oct. 2013 ([http://www.etsi.org/deliver/etsi\\_gs/NFV/001\\_099/001/01.01.01\\_60/g\\_s\\_NFV001v010101p.pdf](http://www.etsi.org/deliver/etsi_gs/NFV/001_099/001/01.01.01_60/g_s_NFV001v010101p.pdf)).
- [8] MCN (Mobile Cloud Networking), EC FP7 Project No. 318109, Jan. 2014 ([www.mobile-cloud-networking.eu](http://www.mobile-cloud-networking.eu)).
- [9] NGMN, *Suggestions on Potential Solutions to C-RAN by NGMN Alliance*, Technical Report, The Next Generation Mobile Networks (NGMN) Alliance, Jan. 2013 ([http://www.ngmn.org/uploads/media/NGMN\\_CRAN\\_Suggestions\\_on\\_Potential\\_Solutions\\_to\\_CRAN.pdf](http://www.ngmn.org/uploads/media/NGMN_CRAN_Suggestions_on_Potential_Solutions_to_CRAN.pdf)).
- [10] B. Haberland, F. Derakhshan, H. Grob-Lipski, R. Klotsche, W. Rehm, P. Schefczik, and M. Soellner, "Radio Base Stations in the Cloud," *Bell Labs Technical Journal*, Vol. 18, No. 1, Apr. 2013, pp. 129–152.
- [11] iJOIN (Interworking and JOINT Design of an Open Access and Backhaul Network Architecture for Small Cells based on Cloud Networks), EC FP7 STREP No. 317941, Jan. 2014 ([www.ict-ijoin.eu](http://www.ict-ijoin.eu)).
- [12] TROPIC (Distributed computing, storage and radio resource allocation over cooperative femtocells), EC FP7 Project No. 318784, Jan. 2014 ([www.ict-tropic.eu](http://www.ict-tropic.eu)).
- [13] Z. Miao, "China Mobile: Successful C-RAN trial in Changsha", in *ZTE Technologies*, Vol. 14, No. 1, June 2012, pp. 26-27.
- [14] ETSI, *Network Functions Virtualisation (NFV): Architectural Framework*, Technical Report ETSI GS NFV 002 v1.1.1, Oct. 2013 ([http://www.etsi.org/deliver/etsi\\_gs/NFV/001\\_099/002/01.01.01\\_60/g\\_s\\_NFV002v010101p.pdf](http://www.etsi.org/deliver/etsi_gs/NFV/001_099/002/01.01.01_60/g_s_NFV002v010101p.pdf)).
- [15] 3GPP, *LTE; Network sharing; Architecture and functional description*, TS 23.251 v. 11.4, Sophia Antipolis, France, Jan. 2013 ([http://www.etsi.org/deliver/etsi\\_ts/23200\\_23299/23251/11.04.00\\_60/ts\\_23251v110400p.pdf](http://www.etsi.org/deliver/etsi_ts/23200_23299/23251/11.04.00_60/ts_23251v110400p.pdf)).
- [16] K. Sundaresan, M.Y. Arslan, S. Singh and S. Rangarajan, "FluidNet: a flexible cloud-based radio access network for small cells," in *Proc. of ACM MobiCom '2013*, New York, NY, USA, Sep. 2013.
- [17] T. Bohnert and A. Edmonds (eds.), *Overall Architecture Definition*, deliverable D2.2, MobileCloud Networking Project, Oct. 2013 (<http://www.mobile-cloud-networking.eu/site>).
- [18] A. Gomes, "CDN and ICN Integration into the LTE EPS Architecture", in *Proc. of 2013 Doctoral Workshop on Distributed Systems*, Les Plans-sur-Bex, Switzerland, July 2013.