Mobile Cloud Networking: Lessons Learnt, Open Research Directions, and Industrial Innovation Opportunities

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I. Mobile Cloud Networking: Myths, Reality, and Lessons Learnt

This keynote speech has the ambition of overviewing some primary lessons learnt and most promising directions for future research/innovation activities in the area of Mobile Cloud Networking (MCN). In the following, the MCN term is specifically used to indicate the exploitation of cloud resources and infrastructures (possibly distributed and federated) to sustain and provision mobility-enabled services to mobile devices, with significant advantages in terms of both cost/investment reduction for mobile infrastructure providers and additional innovative (functional and non-functional) features generated by infrastructure virtualization. Let me note that this definition does not include other potential forms of "mobile clouds" that can combine the innovation directions of mobility and cloud, e.g., exploiting richer and richer mobile devices as cloud-like virtual resources, for instance in the so-called vehicular clouds [1]. The latter approaches are considered out of the scope of this paper and presentation.

In the last years we have experienced a growing industrial interest in MCN as the opportunity to exploit the cloud computing paradigm through Network Function Virtualization (NFV) [2], primarily with the goal to reduce CAPEX/OPEX for future mobile networks deployment and operation. Less than 3-4 years ago there was still a predominant skeptical feeling against this opportunity, mainly substantiated by the risk that a virtualized infrastructure could not reach the levels of service reliability, availability, and quality that are usual for mobile telecommunication scenarios. Now, also after the contribution of 3 years of our research/innovation efforts within the framework of the EU MCN project [3], this initial caution is increasingly disappearing, together with the related false myth of inadequate cloud resource quality. Large experimental campaigns and results from wide-scale industrial testbeds, also accomplished within the MCN project, have demonstrated that it is possible to achieve telco-compliant quality levels via virtualized cloud resources through the adoption of advanced techniques for lazy coordination of distributed cloud resources, for standardized virtualization of network functions, for proactive mobility-aware management and load balancing, and for interoperable orchestration of infrastructure/service components. A few relevant results about the exploitation of the above techniques will be shown in the keynote speech.

Another, less technical, lesson learnt is about the suitability of coupling efficient technical solutions with sound and effective business models, capable of turning the advantages of cloudification/virtualization into market competitive pros. For instance, in MCN we did the basic assumption of the existence of Radio Access Networks (RAN), micro, and macro Data Centers (DCs). Macro DCs are standard large-scale computing farms deployed and operated at strategically selected locations; micro DCs are medium- to small-scale deployments of server clusters across a certain geographic area, for instance covering a city or a certain rural area and as part of a mobile network infrastructure. Ownership and operation of these infrastructure elements can vary. A mobile network operator, for instance, may operate several RANs, mobile core networks, as well as DCs, and thus enjoy full control of all technology domains. Another more advanced example could be a company (e.g., a mobile network operator, a DC provider, or any other enterprise) that acts as end-to-end MCN provider without owning and operating any physical infrastructure. This company would sign wholesale agreements with physical infrastructure owners, for instance mobile network carriers in those geographic areas it wishes to provide access to MCN services. The same would be the case for contracting DC operators in strategic locations and in order to complete a full MCN offering (RAN, Mobile Core, DC). The distinctive aspect of this approach is that a MCN provider exploits the MCN architecture to compose and operate a virtual end-to-end infrastructure and platform layer on top of a set of fragmented physical infrastructure pieces provided by different mobile network and DC owners/operators, thus providing a differentiated end-to-end MCN service (mobile network+compute+storage), not limited to a given geographic area.

The other lesson learnt in these years is that lowering expenses is a common industry practice but ultimately only novel services and business models, with clearly perceivable added

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value, will sustain healthy Average Revenue Per Unit (ARPU). For instance, in MCN we decided to support a more forward-looking advanced vision with the introduction of the previously mentioned MCN provider. Instead of contracting mobile connectivity from one or several mobile operators, a utility provider with demand for mobile communication, compute, and storage services would sign a contract with the MCN provider. It is the MCN provider that maintains contracts with a set of cloud-ready mobile networks and DC providers, thus offering an end-to-end MCN service. This service can offer on-demand, elastic, and metered mobile network + compute + storage services (*-as-a-Service - *aaS), in an end-to-end and transparent way. To this purpose, the infrastructure developed within the MCN project supports the following innovative concepts:

- Wireless-aaS, enabled by Remote Access Network virtualization, with Base Band Units deployed on-demand on elastic Infrastructure-aaS (IaaS) running on top of micro DC close to antennas;
- Evolved Packet Core (EPC)-aaS, i.e., on-demand deployment of distributed EPC instances on top of elastic IaaS on micro and/or macro DC;
- IP Multimedia Subsystem (IMS)-aaS, i.e., on-demand deployment of IMS instances for complementing voice/video services on top of elastic IaaS on micro and macro DC;
- On-demand and elastic content/storage/application distribution services, on top of IaaS on micro and macro DC and exploiting cloud storage services (e.g., the Follow-Me cloud solution [4]);
- End-to-End MCN service orchestration;
- MCN Authentication Authorization Accounting, Service Level Agreements, Monitoring, Rating, and Charging.

Notwithstanding the progresses made in both technical solutions maturity and community awareness about the above technological/business aspects, many research & innovation challenges make the MCN area still widely open for relevant future research, experimentation, and piloting, as briefly pointed out in the following section (due to page length limitations) and as more extensively described in the keynote presentation with practical examples and associated results.

II. Open Research Directions and Industrial Innovation Opportunities

Even if relevant results have already been achieved in controlling and, to some extent, guaranteeing quality of service in virtualized MCN services, several research challenges related to high availability, resiliency, quality, and efficient exploitation of distributed cloud resources are still open, primarily:

- ***Fog-enabled federated management*** - Is it possible to efficiently deploy and federatedly manage densely interconnected and decentralized cloud infrastructures, by possibly exploiting fog computing approaches that dynamically move (partial) MCN functions to the edge of the network in order to take local decisions and optimizations?
- ***Scalability and quality for data-intensive applications*** - Which effective and efficient solutions are available to address technical challenges about scale, quality, and privacy/security, also by considering the innovative elements posed by data-intensive applications deployed over federated environments, such as in the case of MCN for smart cities or wide-scale cyber-physical systems?
- ***Efficient mobile edges for resiliency*** - How to exploit mobile edge computing towards disaster resilient and emergency robust MCN solutions? How should it be efficiently combined with DC networking virtualization?
- ***Local resource efficiency and distributed orchestration*** - Which novel algorithms and techniques for resource efficiency and composition? For instance, adaptive scheduling algorithms and orchestration frameworks that can take into consideration dynamically changing patterns for service demand and mobility, as well as network state and application confidentiality levels. And, similarly, what about novel adaptive application offloading?

Analogously, about immediate industrial applicability of MCN solutions, in several sub-areas with specific performance/functional constraints we are far from ready-to-deploy frameworks. Particularly open innovation challenges of industrial relevance include:

- high-availability by design, in particular in the case of cloud networking in federated infrastructures;
- cost-efficient scalability;
- QoS differentiation with reasonable guarantees under dynamically changing (in both time and space) load profiles;
- Prototyping and demonstrating wide-scale pilots that show the advantages of MCN techniques in "hard" application scenarios, such as federated mobile public safety networks, with specific challenges in terms of reliability and privacy.

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