V–Cell: Going Beyond the Cell Abstraction in 5G Mobile Networks

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***Abstract*—Past years have witnessed the surge of mobile broadband Internet traffic due to the broad adoption of a number of major technical advances in new wireless technologies and consumer electronics. In this respect, mobile networks have greatly increased their availability to meet the exponentially growing capacity demand of modern mobile applications and services. The upcoming scenario in the near future lays down the possibility of a continuum of communications thanks also to the deployment of so called *small cells*. Conventional cellular networks and the small cells will form the foundation of this pervasive communication system. Therefore, future wireless systems must carry the necessary scalability and seamless operation to accommodate the users and integrate the macro cells and small cells together. In this work we propose the *V–Cell* concept and architecture. *V–Cell* is potentially leading to a paradigm shift when approaching the system designs that allows to overcome most of the limitations of physical layer techniques in conventional wireless networks.**

I. Introduction

Recent years have witnessed the surge of mobile broadband Internet access, thanks also to recent advances in new wireless technologies and consumer electronics (e.g. smart phones). By 2020, a 1000–fold increase in the traffic originating from new mobile applications and services (e.g. HDTV, machine-to-machine) is expected [1]. So far cellular networks have coped with this dramatically growing trend by moving from a macro–cell vision (i.e. large cellular base stations) of the network to a scenario where cells with a smaller radio fingerprint (pico–cell, femto–cell etc.) overlap with the macro cell in order to boost up to the expected network capacity.

Such an approach while sufficient for the moment is bound to hit several roadblocks in the near future. In fact, if on the one hand these networks, called Heterogeneous Networks (or HetNets) can indeed alleviate macro cells from part of the burden generated by mobile users, on the other hand they also increase the signaling between neighboring cells. In addition, the energy efficiency of the entire network is significantly reduced. The increased signaling, is a direct consequence of the highly distributed control path that characterizes modern cellular networks, namely the Advanced UMTS Long Term Evolution, or LTE-Advanced (LTE-A). The increased power consumption is mainly due to the lack of coordination between neighboring cells (i.e. macro and small cells) that are required to stay online even when there is no traffic.

Alongside the technical issues, there are also a number of economic challenges that calls for a significant re–factoring of the mobile network in order to cope with the decreasing Average Revenue Per User (ARPU) and the increasing network deployment (CAPEX) and operation (OPEX) costs. Operators are evermore interested in tapping into the revenues generated by modern mobile applications (e.g. Netflix, YouTube). One possible path toward this goal goes trough an increased integration between the mobile network and the cloud, dynamic caching of content at the cellular Radio Access Network (RAN) level as well as is just one example in this direction. Moreover significant CAPEX and OPEX savings can be obtained through a more efficient spectrum usage and infrastructure sharing and, on a longer time–frame, also through sharing of spectrum between carriers. Finally, a backhaul design departing from today's very centralized architecture is seen as another stepping stone to increase mobile network availability.

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Since their inception decades ago, mobile networks have relied on the cell as their fundamental abstraction. However, the increasingly higher density of radio terminals inside the RAN and its heterogeneous nature in terms of radio, backhaul and core technologies motivates the need to revisit the entire concept. In this work, we argue in favor of a Virtual Cells abstraction, or simply *V–Cell*, where all the resources made available by a group of heterogeneous cells (macro, pico, and femto), are considered as a single pool of resources that can be managed by a logically centralized Software–Defined network controller, or Software–defined RAN (SD–RAN).

From the user equipment (UE) standpoint the pooled resources in a *V–Cell*-based mobile network, will represent logically a single big macro cell. On the other hand, by relying on a global view of the underlying network, the SD-RAN controller will be able to dynamically schedule resources across the entire pool of physical cells. The final goal of this approach is to revert back to a logically sparse network (as envisioned by 3GPP) where pools of heterogeneous cells appear to each other and to the UEs as legacy macro cells. Moreover, leveraging on its SDN nature, *V–Cell* will allow for pools of resources that will be dynamically changed at runtime allowing the network operator to adapt the configuration to the changing demand coming from the users.

The rest of the paper is structured as follows. Related work is discussed in Sec. II. System architecture is sketched in Sec. III while se cases are introduced in Sec. IV. Finally, we discuss the challenges of realizing *V–Cell* in Sec. V.

II. Related work

In this section, we summarize the most relevant works that investigate the idea of simplifying the data–plane and control–plane of wireless networks with the aim of empowering the network operator with a set of powerful abstractions and programming primitives to effectively and efficiently control and manage the network.

In [2], a network architecture for the enterprise (Ethane) is presented. Ethane couples flow–based Ethernet switches with a centralized controller that manages the admittance and routing of flows. Thus, all complex functionality, including routing, naming, policy declaration and security checks are performed by a central controller rather than in the switches. Based on the real implementation results the paper concludes that a single Controller could manage several thousand of machines and an Ethane switch will be significantly simpler, smaller, and lower-power than current Ethernet switches and routers.

Similarly the authors of [3] decouples mobility from the physical network. The authors propose *OpenFlow Wireless* a mobile wireless network platform enabling experimental research and realistic deployments of networks and services using virtualization. OpenFlow Wireless uses OpenFlow [4] to separate control from the data-path through an open API in order to create network slices and provide isolation among them. This *OpenFlow Wireless* also allows network administrators to create a centralized control of their wireless network.

In [5], authors argue that SDN can simplify the design and management of cellular data networks, while enabling new services. The authors sketch out changes and extensions to controller platforms, network switches, and base stations to enable software defined cellular networks. This work is deeply extended in [6], where SoftCell a scalable architecture that supports fine–grained policies for mobile devices in cellular core networks using commodity switches and servers is presented. SoftCell enables operators to realize high-level service policies that direct traffic through sequences of middle–boxes based on subscriber attributes and applications. SoftCell also aggregates traffic along multiple dimensions at different switches in the network in order to minimize the size of the forwarding tables. Results shown that SoftCell improves the scalability and flexibility of cellular core networks.

In [7] OpenRadio a novel design for a programmable wireless data–plane is presented. The objective is the refactoring of wireless protocols into processing and decision planes. The processing plane includes directed graphs of algorithmic actions while the decision plane contains the logic which dictates which directed graph is used for a particular packet. This allows operators to assemble a protocol only expressing decision plane rules and corresponding processing plane action graphs. Another approach toward the RAN simplification, called CloudIQ, is discussed in [8].

Similarly, authors in [9] argue that distributed control plane is suboptimal in order to allocate radio resources, implement handovers, manage interference and balance the load. They propose SoftRAN, a software–defined centralized control plane for radio access networks that abstracts all base stations in a local geographical area as a virtual big-base station. In the paper a preliminary design and architecture of SoftRAN, use cases, feasibility and scalability aspects are also described.

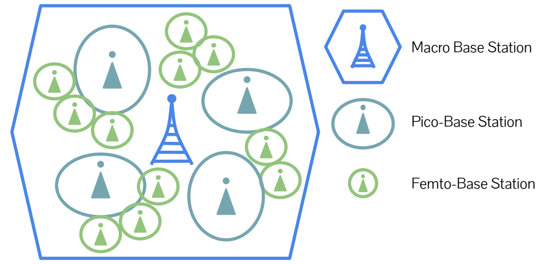

Fig. 1. Current best practices in cellular networks account for the increased demand for data capacity by deploying smaller cells over the area previously covered by a single macro–cell.

While these recent literature demonstrates continuing interest at addressing the complexity of future mobile networks, the new design criteria of 5th Generation of cellular networks (termed as 5G networks) will require disruptive design choices in managing the heterogeneous network deployments. The *V–Cell* concept aims at re–thinking the current mobile networks taking into account technological enhancements such as storage capabilities and programmable multi radio access technology (Multi–RAT) devices which can enable a variety of new business models and services that are likely to appear in the market with the deployment of 5G networks. In the next section, we provide an overview of potential use cases and we discuss how the *V–Cell* concept will be beneficial in realizing such novel usecases for 5G networks.

III. System Design

In mobile networks, the RAN is responsible for globally managing the radio resources at the various base stations in order to deliver connectivity to the UEs. In order to cope with the increasing demand of bandwidth resources for data transmission (in fact voice traffic has remained relatively stable during the last decade), mobile network operators are progressively moving away from sparse RANs composed of few large macro–cells to a dense RAN composed of a multitude of overlapping macro and small–cells. However, 4G cellular networks have not been designed for such dense deployments. In particular, their highly distributed control allows base stations to perform radio resource management tasks autonomously and to handle user mobility in a distributed fashion. Such architecture fits well a scenario where base stations are sparse and the decisions they take cannot affect neighboring cells (since they are far apart from each other). On the contrary, the progressively higher density inside the RAN is causing an increasing burden on the inter base station signaling and on the network backhaul. This so called *densification* of the RAN is shown in Fig. 1.

The RAN as whole performs basically three main tasks: (i) Mobility Management, (ii) Radio Resource Management, and (iii) Power Management. Such tasks are tightly coupled and effectively implement the control of an LTE-A mobile

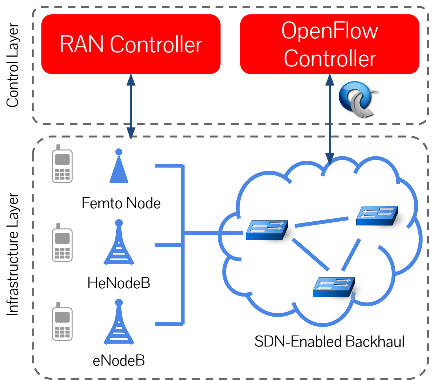

Fig. 2. The *V–Cell* system architecture. The RAN controller provides a framework on top of which control algorithms can operate. The SDN–enabled backhaul allows such algorithms to jointly account for RAN congestion.

network. Due to the volatile nature of the wireless medium, the channel quality for each UE can vary significantly across the resource space and, as a result, resources must be carefully scheduled in time, space, and frequency as well as the power level across the various cells. Moreover, the various base stations can, and generally do, exploit heterogeneous backhaul technologies, such as fiber, copper, point–to–point wireless link (possibly the 60 GHz band in the future). As a result, mobility decisions taken in the RAN can seriously affect the traffic distribution over the backhaul link.

It is our standpoint that LTE-A networks must move away from the current cells abstraction toward a continuum of networks resources that can be pooled at a logically centralized RAN controller where control decision can be taken starting from a global view of the network and taking into account also the impact that such decisions have on the backhaul. *V–Cell* proposes an architecture leveraging a logically centralized controller that replaces the distributed control plane currently seen in LTE-A networks and where all resources made available by a pool of base stations are rearranged into a single large resource space.

The *V–Cell* high level system architecture is sketched in Fig. 2. From a conceptual perspective the *V–Cell* controller appears to the RAN as an OpenFlow controller appears to a traditional SDN–enabled network. However, while in the case of an OpenFlow network the elementary forwarding abstraction is the flowspace, i.e. an aggregate of packets sharing a common pattern in the header space supported by the OpenFLow protocol, in the case of the *V–Cell* controller the basic abstraction is the time and frequency orthogonal frequency division multiple access (OFDMA) resource blocks space exploited by 4G technologies.

A. The V–Cell Architecture

The *V–Cell* architecture is based on a centralized architecture that replaces the distributed control plane currently implemented by 4G mobile networks. The *V–Cell* architecture abstracts a pool of cells covering a certain area as a single large virtual cell. Notice that with the term *cell* we refer to both macro– and small–cells.

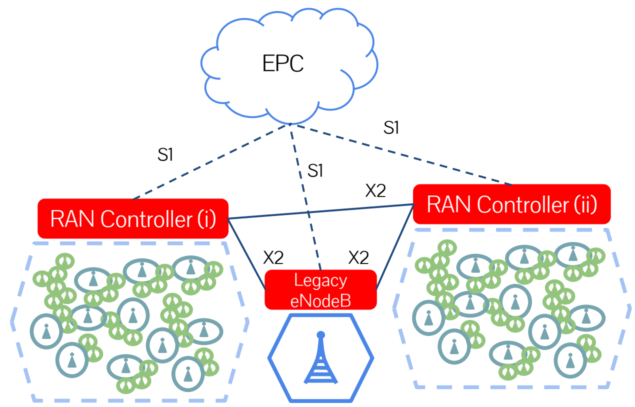

Fig. 3. The *V–Cell* network architecture. The *V–Cell* SD–RAN exploit the standard X2 interface toward other eNodeBs and/or *V–Cell* SD–RAN controllers, and the S1 interface toward the LTE EPC.

The *V–Cell* consists of a single SD–RAN controller and multiple base stations, named in this work Radio Termination Points (RTPs). This change of terminology is motivated by the fact that our architecture can exploit both full-featured 4G LTE Base Stations (the eNodeBs), customarily used in macro cells, as well as simpler small–cells base stations (the HeNodeB), and Remote Radio Heads. The set of RTPs coordinated by a single SD–RAN is named *Pool*. The SD–RAN controller exploits custom protocols in order to communicate with the RTP in its Pool. The controller implements also the standard X2 and S1 interfaces in order to communicate with, respectively, other eNodeBs (eastbound) and the LTE EPC (northbound). Such an architecture depicted in Fig. 3 enables incremental and allows interoperability with legacy networks.

Finally, the soft binding between RTP and SD–RAN controller allows the operator to actually move an RTP from one pool to another at run–time. The usefulness of such feature will become apparent in the next section where the handover model exploited in *V–Cell* will be described.

B. Virtual eNodeB

In an LTE network the smallest granularity at which resources are allocated to an UE is the resource block. A resource block consist of twelve OFDMA sub–carriers and is 1 ms long. In the *V–Cell* architecture all the radio resource blocks are abstracted into a single large radio resource space and are scheduled by SD–RAN controller. From the operator perspective the entire pool of cells can be considered as a legacy macro cell coordinated by a legacy eNodeB. As a matter of fact we envision the SD–RAN controller to implement the standard X2 interface in allowing interoperability with legacy deployments.

A central primitive of the *V–Cell* architecture is the Virtual eNodeB (VeNB). A client attempting to join a *V–Cell* network will trigger the creation of a new VeNB. Such VeNB has a cell reference ID that is specific to the newly associated client. As a result, in *V–Cell* every UE receives a dedicated VeNB which basically translate into giving each UE the impression of having its own dedicated eNodeB. As a result each physical base station *hosts* as many VeNB as the number of UEs currently communicating with it. Removing a VeNB from an RTP and instantiating it on another RTP effectively results in handing over a wireless client to the other RTP *without* the need to perform a full 4G handover. The UE will continue to sense both the physycal base stations cell IDs and their VeNBs. The rationale behind such choice is that in 4G networks base stations can actually request the UE to perform channel quality measurements on cells different from the ones to which they are currently connected. By allowing cells to still broadcast their physical reference signal we enable the SD–RAN controller to request the UE to assess the channel quality toward other RTPs in its Pool. As a result of these measurements, the SD–RAN can decide to migrate a VeNB from one RTP to another.

Our design effectively turns a *V–Cell* Pool into a no–handover zone where active *legacy* UEs can roam around without performing any handover while always exploiting a consistent connection with the network. Such feature provides a dramatic advantage in dense networks where the standard 4G implementation would normally result into a severe signaling overhead generated by the numerous handovers that are inevitable as the cell sizes becomes smaller. On the other hand, with *V–Cell* the operator can define a no–handover zone (the Pool) according to the actual traffic conditions in terms of *both* number of wireless clients and type of traffic. Another immediate advantage of such solution is that by centralizing radio resources scheduling it will be possible to actually power–off the parts of the network that are not needed, thus bringing more fine–grained control on the energy management of dense 5G networks.

C. Resource Pool Concept

Here, we explain the proposed Resource Pool concept and the role that the VeNB and SD–RAN controller play in it. We consider a standard cellular network where N is the set of $n = |N|$ base stations and where U is the set of $u = |U|$ users served by them. The downlink bandwidth of each base station $i \in N$ is divided into a maximum of r_i RBs. Each RB can be assigned to at most one UE every Transmission Time Interval (TTI) t, which is the smallest granularity in time at which resources can be allocated in a 4G network per data communication and is 1–ms long. At the network level, base stations are grouped into pools P, where for each pool $p \in P$ it holds that $p \subseteq N$ moreover each base station may belong to one pool only, i.e. the intersection between all the sets of pools is the empty set. Thus, the r_i RBs of each base station are aggregated in a single *3–dimensional* matrix of RBs in time (T), frequency (F) and space (A), namely the *Resource Pool*. The *Resource Pool* concept is sketched in Fig. 4. In the figure, the green square represents a single RB while the black square represents the RBs assigned to the VeNB$_i$ across time. As it can be seen, the VeNB follows the UE through the network eliminating the need for LTE handovers across the whole *V–Cell*.

Since each VeNB represents a single UE, the minimum entity to be served by the SD–RAN controller is the VeNB. Therefore, the SD–RAN controller creates new VeNBs as soon as the UE has been authenticated and associated to the Network. Having the *Resource Pool* at the RAN controller level allows to centralize the control–plane and simplify it at the same time. For example, the SD–RAN controller can allocate resources across the totality of RBs managed by a certain *V–Cell*. Thus, the main role of the RAN controller is to allocate radio resources, manage limited spectrum, interference and power allocation and balance load inside the *V–Cell* across the various VeNB. Notice that the *Resource Pool* can change from one TTI to another due to the SD–RAN controller decisions based on map frequencies and interferences, resources needed by coverage area, energy consumption and others.

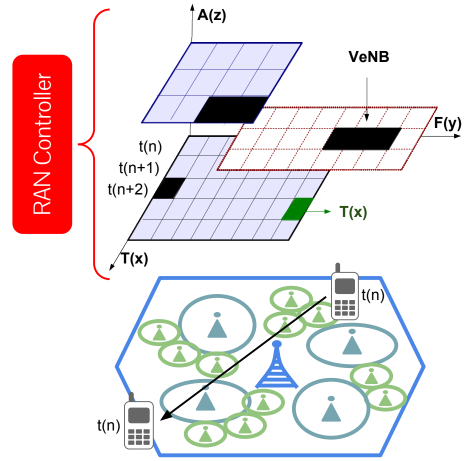

Fig. 4. The *Resource Pool*. The VeNB follows the UE through the entire network eliminating the need for LTE handovers across the whole *V–Cell*.

The VeNB also plays an important role inside the *V–Cell*, as for example it takes care of tracking and following the UE through the network in order to eliminate the handover procedures. This is possible due to (i) light–weight and virtual nature of the VeNB, and (ii) the flexibility of the SD–RAN controller for easily reallocating resources to the VeNB across the *Resource Pool*. Thus, the dedicated VeNB asks the SD–RAN Controller for new resources in a specific area and informs the mobile UE when and where switching to another RTP. The VeNB is also responsible for retransmission handling and multiplexing of data flows for the UE.

IV. Use Cases

In this section, we explain two specify uses cases which are beneficied by the proposed *V–Cell* approach.

A. Prosumers

One potential use case which is attracting the attention of the academia and industry is the so called *prosumer* approach. The term prosumer was firstly used by Alvin Toffler in 1980s, in his book *The Third Wave*, defining it as someone who blurs the distinction between a *consumer* and a *producer*. As stated in [10], the prosumer segment is currently estimated to be around 4.5% of the total population in the US. However, its influence is growing rapidly and it is nowadays well-recognized that more attention must be paid to the under-served prosumer market as well as how to address it better. The term prosumer can also be understood as a form of advanced consumer. In this respect, some examples of prosumers' business can be found in home depots, specialized channels in the digital TV as well as the offer of Internet–based services. However, in the 4G networks and beyond the prosumer ecosystem and its ever–increasing role is expected to redefine some of the existing business models. Prosumers are not exclusively meant to be *business oriented* people but can also be seen as *content information producers*. However, the current trend is to classify the prosumer as somebody able to offer localized and customized services for the clients offering a high quality–of–experience (QoE). For example, it is envisioned that a prosumer could be able to deploy hardware, manage the connectivity locally and offer bandwidth to other users in a the two-tier network including small–cells. In this scenario, the network operators shall be able to monitor and to some extent control the small–cells operations in order to guarantee the required QoE upon establishing a detailed agreement with the prosumers. The implementation of the *V–Cell* concept goes in the direction of this overall goal giving a practical means of managing the capacity demand at runtime. Furthermore, *V–Cell* offers seamless connectivity and it endows prosumers with easy-to-use solutions to manage their networks and/or provide their services.

B. Dynamic Caching

Another application where the adoption of *V–Cell* can be mutually fruitful is that of *dynamic caching* [11]. As a matter of fact it is envisioned that in scenarios pertaining to 5G networks and beyond the radio access network could become the bottleneck in the delivery of modern web services and content [12]. The reasons that lie behind this consideration can be traced back to the booming of small–cells deployments (i.e. very high spatial packing of radio transmitters) and possibly the adoption of wireless backhaul links (that is in opposition to typical backhaul links that are made of optical fiber or Ethernet cables). The concept behind Dynamic Content Caching is to store frequently accessed content near the end–users and more in particular at the edges of the mobile network, i.e. at the RAN. In this way, further requests for the same content can be redirect at the RAN cache without putting further burden on either the front– or the back–haul. Dynamic caching can become a useful way of storing popular content (e.g. latest movies in a movie theaters or advertisement) that is available in the same area of the end user. Pushing the concept of caching toward the end users, the application of dynamic caching techniques can also be appealing to leverage new forms of social networking (e.g. dynamic caching applied to content sharing among users during sport events for example). People located in proximity could form a local area community in which people might be able to transparently upload/download popular content to/from other users, thus further reducing the overall traffic transported not only by the backhaul but also at the base station. The combination of the *V–Cell* concept and dynamic caching can dramatically reduce the stress on the backhaul with the SD–RAN controller acting as a content caching manager.

V. Discussion

The current 4G mobile networks and beyond are going trough a process of densification of the RAN, where more and more macro, micro, and pico base stations are deployed in to order to support modern data hungry mobile applications. Such an approach does not cope well with the highly distributed control plane that characterizes current mobile networks. As a matter of fact these protocols perform well in sparse deployment where few large macro cells provide the necessary capacity and do not overlap in space. On the other hand such protocols are not effective is dense networks where the decisions taken from a base station do affect the neighboring cells and where the small cell size triggers numerous handovers.

In order to account for this change of trend in the deployment of mobile networks we have proposed a new software–defined centralized control plane for radio access networks that effectively abstracts all the resources made available by a pool of base stations into a single, large resource pool, namely the *V–Cell*. The *V–Cell* will act as a means of efficiently blurring the multi-level HetNets envisioned for 5G networks by providing the architectural means for scaling 5G deployments on-the-fly. Such design basically restore the sparse cell assumption at the base of current cellular architectures while at the same time providing a mean for incremental and backward compatible deployments. We are currently validating the *V–Cell* concept using a custom 4G network simulator and we also plan to move to a proof–of–concept implementation exploiting commercial Software Defined Radio platform.

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