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Published in:
IEEE Access

Published: 01/01/2016

Document Version:
Final Published version, also known as Publisher's PDF, Publisher's Final version or Version of Record

Publication record in CityU Scholars:
Go to record

Published version (DOI):
10.1109/ACCESS.2016.2563518

Publication details:
https://doi.org/10.1109/ACCESS.2016.2563518

Citing this paper
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Low-Cost On-Demand C-RAN Based Mobile Small-Cells

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This work was supported by the European Community’s Seventh Framework Programme [FP7/2007-2013] through the CRS-i Project under Grant 318563.

ABSTRACT Although 4G networks are vastly being deployed around the world, the exponential growth of mobile traffic and the requirements of upcoming services are further pushing the limits on current mobile networks; hence, worldwide research interests have shifted toward 5G paradigm. But 5G networks are not to be deployed until 2020; hence, there is a need for solutions to address increasing demands of current networks, without incurring huge costs on operators. In this paper, we discuss low cost innovative networking scenario, which can be built using available 4G technologies, yet continue to exist within the 5G paradigm when deployed. This paper proposes on-demand deployment of mobile small cells, using either user mobile handsets or remote radio units. The front hauling from the core network to the small cells exploits disruptive technology trends, which are expected to play roles within the 5G paradigms, including the cloud-based radio access network, and self-organizing networking. This paper discusses the envisioned scenario, shows how it can be built on expected 5G technologies trends, presents preliminary results that show the benefits gained from such deployment, and, finally, details the foreseen open research challenges that need to be addressed.

INDEX TERMS 5G, backhaul, C-RAN, LTE-advanced, mmWave.

I. INTRODUCTION

Despite the wide deployment of 4G systems worldwide, the massive growth of mobile traffic is still pushing the limits on current mobile technologies. Traffic from wireless and mobile devices will exceed that from wired devices for the first time by 2019. The global Internet traffic in 2019 will be 64 times the entire global Internet in 2005 [1]. The steady increase in mobile traffic, along with the more sophisticated broadband services, is forcing mobile standards to provide tighter integration between wireless technologies and higher speeds, thus moving further towards a new generation of mobile communications: the 5th Generation (5G). The interests of stakeholders and academic researchers are now focused on 5G paradigm. Although 5G is not expected to penetrate the market till 2020, many properties and technology trends have been widely accepted to form part of the highly anticipated 5G [2], [3].

By year 2020, mobile networks will have to support $1000 \times$ times higher mobile data volumes, with up to 100 (even 10,000 [2]) times the number of connected devices [4], [5]. Not only that, but the nature and services of devices will vary due to the introduction of new applications, such as smart cities and e-Health [6]. The increase in number of devices and traffic, the variation in service and device nature, along with the pressure on operation and capital cost and energy efficiency are all putting stringent limits on the requirements of the design of future generation of mobile networks. It is widely accepted that incremental enhancements of current networking will not achieve or come close to meeting the requirements of networking in 2020 [3]. This has led to the adoption of a new generation 5G, which have to be disruptive and not incremental.

Certain technology trends have been widely accepted as integral pieces of the jigsaw of 5G. 5G is foreseen as a multi-tier heterogeneous platform, which will not be backward compatible but rather inclusive of legacy systems such as 3G and 4G [2], [3]. The heterogeneity of 5G will also include a plethora of different cell types (macro, pico, Femto, etc.), as well as other types of communications, such as Peer-to-Peer (P2P) and machine-to-machine (M2M).
Following the same trend, densification will play a main role in the concept of 5G, where the number of cells is expected to multiply and the density of devices per unit area will 1000 times multiply [2]. Among other technology trends to play a role within 5G are cloud-based radio access network (C-RAN), and self-organizing networks (SONs).

Although the vision of 5G is getting clearer every day, 5G networks are not expected to be deployed till 2020. Till then, mobile traffic will continue to increase pushing the burdens on current deployed networks. However, mobile operators are reluctant to invest in expensive solutions, which may become obsolete once 5G is finalized. Building on this argument, in this paper we propose a low cost solution, which is built on current technology trends, expected to be adopted by 5G. The solution exploits the concept of small cells, but using mobile handsets that can be setup autonomously on-demand as small cells. The envisioned scenarios further exploit C-RAN concept, and SONs, to make the most out of on-demand mobile small cells. The main advantages of such solution are its low cost, ease of adoption, in addition to the wide acceptance of such solutions to continue to form part of the 5G paradigm; hence mobile operators would be encouraged to adopt such solution. In order to show the relevance of adopted solutions to 5G paradigm, the paper starts with presenting a brief vision of the 5G system. The paper then describes the proposed solution through describing the foreseen scenarios, and technology choices. The paper then presents preliminary simulation results showing the advantage of adopting such solution, including gains in SINR, higher UE average throughput and better spectral efficiency. Finally, to fully exploit the benefits of the solution, certain challenges need to be addressed. We identify those research challenges and discuss them at the end of the paper.

The remainder of this paper is organized as follows. Section II provides the widely accepted vision of 5G, including the expected service and capabilities that have to be offered and adopted technology trends. In Section III, we describe the proposed solution scenarios, highlighting the advantages of such technology choices. Section IV presents some preliminary performance evaluation using simulations, showing the advantage of such concept in achieved spectrum efficiency and higher throughput. In Section V, some futuristic approaches, which can be implemented to further enhance the proposed solution, are listed. Section VI discusses the open research questions that arise from adopting such scenario, which need to be answered, if such solution is to achieve its full foreseen benefits. Section VII concludes the paper.

II. 5G VISION

The fifth generation (5G) wireless networks are rapidly evolving, but 5G systems are only expected to be deployed by year 2020 [2], [3]. Although, it is yet sometime till 5G standards are consolidated and finalized, there is a wide acceptance of technology trends that will definitely form part of the 5G paradigm, as well as the features and performance that have to be supported [2], [3]. This section draws a picture of what to expect from 5G, in addition to a brief survey of technology trends to be adopted. We do not claim that we are presenting a complete vision of 5G, but rather showing how our proposed solution provides a low-cost solution that can be built on existing technologies of 4G, while continuing to be relevant when 5G systems are deployed. This way, mobile operators would not be reluctant to adopt such concept, which provides a step towards delivering 5G services, without incurring much costs on non-relevant technologies, especially that the solution does not need high capital costs nor extensive network planning.

Beginning with the envisioned environment of 5G, it is clear that mobile traffic is growing at unprecedented rates and will continue to grow. Traffic from wireless and mobile devices are extrapolated to exceed that from wired devices by 2019 [1]. In addition to traffic increase, 1000x throughput improvement is expected with 10 Gb/s cell data rate [2]. User data rates are anticipated to rocket, reaching 10 to 100 times that of current 4G [6]. Latency is required to be reduced down to 1 ms end-to-end [3]. All these enhancements in performance have to be coupled with a huge increase in number of mobile devices, reaching 100 (10,000 [2]) times the number of current connected devices [4]–[6]. It is anticipated that the number of connected devices will be three times the global population in 2019 [1]. That huge number of connected devices will come with new advanced and diverse services, which 5G networking has to support with the best quality of experience based on the nature of the device and its functionality [2]. 5G networks have to support all those services, while keeping the costs low and taking into consideration energy efficiency, especially due to the existence of certain devices with very limited energy capacity without easy access to charging options (i.e. sensors).

Based on such vision of networking environment around 2020, it is so clear that incremental enhancements of current 4G will not be sufficient to meet all the demands of such complicated and diverse system [3]; hence the need for a new disruptive generation of mobile communications: the 5G. In order for 5G to meet those stringent requirements, main stakeholders and players have widely accepted certain technology trends to play a role within the 5G paradigm. In the rest of this section, we will list some of those relevant technology trends to show how the proposed solution follows the 5G path.

One of the mostly accepted technology trends of 5G is densification. Future cellular networks are expected to be hugely densified, with the adoption of multi-tier heterogeneous network, including macro-cells, huge number of small cells, relays, remote radio units (RRUs), device-to-device communications (including machine-to-machine M2M) [2]. 5G is foreseen to be a heterogeneous networking platform, where legacy systems like 3G and 4G coexist with 5G new paradigms [3]. Our solution is built on this concept, where densification is achieved through the deployment of on-demand mobile small cells (which can be RRUs or...
C-RAN is a disruptive concept in cellular networks. In current 4G, radio and baseband processing are performed integrally within BSs, while the coordination between BSs is actualized over X2 interface. Using C-RAN, the baseband processing can hence be executed in the cloud. It is widely accepted that C-RAN will play a role within the next generation 5G paradigm [2]. Our concept utilizes C-RAN for interference management in multi-tier architecture.

Despite the major enhancement in performance that can be achieved using disruptive technology trends in 5G, the varying dynamics of the network will increase meaning that the optimal operating point is unsustainable leading to ineffective use of network resources over time. Hence, the appearance of SONs represents a continuation of the natural evolution of wireless networks. SONs are expected to exist within 5G [2]. Due to the high randomness of devices within cellular networks, automated network management is crucial in the proposed solution. The solution takes advantage of SONs concept to autonomously manage and control on-demand mobile small cells, to keep the network almost always operating at optimal point.

In conclusion, 5G paradigm is yet to be finalized; however certain 5G properties and technology trends have been identified and widely accepted. We built on such vision using technology trends foreseen to be adopted by 5G, to provide a low cost solution that can be adopted with current existing technologies without excessive costs nor network planning, yet will continue to exist once 5G is deployed.

III. C-RAN BASED MOBILE SMALL CELL SCENARIO

In designing and planning small-cell deployments in HetNets, mobile operators come across two significant problems [7]: i) How to transport traffic from the small-cell at the edge of the mobile network? ii) How to manage the radio access network (RAN), specifically, interference and resource management? However, these are two separate research problems that are tightly coupled, because to a certain extent how the network manages traffic distribution defines the techniques the operator can successfully utilize to reduce and coordinate interference. The edge link that connects small-cells to the rest of the network may use different technologies: wired (e.g. fiber) or wireless (e.g. LOS or NLOS; licensed or license exempt spectrum; point-to-point or point-to-multipoint; Microwave or mmWave). mmWave has already been standardized for short range services and deployed for application such as small cells backhaul. Therefore, it could lead to unrivaled data rates and a completely different user experience if deployed for broadband applications, either for backhaul or fronthaul distribution.

Traditionally, the backhaul segment connects the RAN to the rest of the network, where the baseband processing takes place at the cell site. However, the notion of the “fronthaul” access is gaining interest, since it has the potential to support remote baseband processing based on adopting a C-RAN architecture that aims to mitigate interference in operator deployed infrastructures; this eases significantly the requirements in interference aware transceivers. This is why our proposed solution is based on C-RAN for interference mitigation. The emergence of wireless fronthaul solutions widens the appeal of fronthaul for small-cell deployments, because fiber – the technology typically used for fronthaul – is too expensive or just not available at many small-cell sites.

In this paper, we present an advanced scenario, which can be further enhanced using envisioned 5G use cases. To be relevant, we start from how small cells are deployed and managed in today’s mobile networks; i.e. how small cell deployment is defined according to 3GPP, as follows.

A. 3GPP SCENARIO: SMALL CELL DEPLOYMENT

When using a backhaul architecture, an integrated small-cell (antenna, wireless transceiver, plus baseband) is connected to an aggregation point – i.e. a macro cell or other location that is connected (typically by fiber) to the mobile core, as shown in Fig. 1.

Since the pico-cell processes the RAN traffic, the operator can use many solutions for backhaul, including fiber or other wireline technologies, or wireless links. Wireless links may include LOS (mmWave) or NLOS (Microwave) bands; point-to-point, point-to-multipoint or mesh topologies; and licensed or license-exempt bands. To emphasize, this is the deployment network operators’ use in today’s networks to deliver data services at low cost, as shown in Fig. 1. In this ‘‘infrastructure based’’ multi-tier deployment, the pico-cell overlay network exploits a backhaul service to deliver high speed services at relatively low cost, while the typical macro-cell network continues to deliver standard lower data rate services over wide area coverage.

FIGURE 1. Legacy 3GPP small cell deployment.
The limitation with such system is the effect of co-channel interference between tiers as well as the random deployment of small cells.

This deployment scenario has spurred interest towards technology enhancement techniques such as COMP transmission [8] and interference management approaches such as the Almost Blank Space approach [9]; both of which are already standardized and form a pivotal part of the LTE-A architecture. In the former, COMP is used to control interference between clusters of macro-cells, as well as providing coverage at the cell edge; whilst the latter approach is used to manage interference between tiers by switching off radio resource space in the macro-cell, when the pico-cell (small cell) is transmitting.

**B. ENVISIONED SCENARIO: C-RAN FOR INTERFERENCE MANAGEMENT IN MULTI-TIER INFRASTRUCTURE NETWORKS**

Future emerging scenarios in small cell deployment are heading towards the notion of cloud radio. C-RAN is a novel mobile technology that separates baseband processing units (BBUs) from radio front-ends such as RRUs. In this technology, BBUs of several base stations are positioned into a central entity, where the radio front-ends of those BSs are deployed at the cell sites [10]–[12]. Therefore, this new framework unfolds a new paradigm for algorithms that need centralized and cooperative processing.

The fronthaul enables a C-RAN architecture, in which all the BBUs are placed at a distance from the cell site. The fronthaul transports the unprocessed RF signal from the antennas to the remote BBUs. While the fronthaul requires a higher bandwidth, lower latency and more accurate synchronization than backhaul, it enables a more efficient use of RAN resources, that coupled with legacy interference and mobility management tools, can significantly minimize interference in the structured part of the network, including pico-macro cell interference. The general C-RAN architecture using fronthaul technology, and associated research challenges are illustrated in Fig. 2. The architecture consists of three main components, namely (i) centralized BBU pool; (ii) remote radio units (RRUs) with antennas; (iii) Transport link, i.e. fronthaul network which connects the RRU to the BBU pool.

In the proposed envisioned scenario, RRU can be substituted by any mobile device connected to the mobile network and owns the required resources to perform the functionality of small cell.

The RRU (i.e. mobile small cells) transmit the RF signals to UEs in the downlink or forward the baseband signals from UEs to the BBU pool for further processing in the uplink. The BBU pool is composed of BBUs, operating as virtual base stations to process baseband signals and optimize the network resource allocation for one RRU or a set of RRUs. The fronthaul links can also be formed using different technologies as mentioned earlier, whether wired or wireless, with all their variability. Introducing C-RAN approach provides several new advantages, namely delivering high speed connectivity through network deployed small cells, as well as means for mitigating interference.

We introduce the notion of mobile small cells, where the mobile handset adopts the role of access point or remote radio unit. This shifts the philosophy of legacy mobile networks from purely being network centric towards being device/user centric. Mobile devices are now seen as a pool of additional network resources to be used by the operator to extend network coverage on demand. On a broader perspective, the separation allows new ways for sharing infrastructures owned and deployed by different operators; that can be managed/operated by the control plane according to the specific set of commercial rules under a common agreement [13].

In the envisioned scenario, the control and data plane are first split. The macro-BS proves the signaling service for the whole area and have these mobile small cells specialized towards delivering data services for high-rate transmission with a light control overhead and appropriate air interface (mmWave could be the best option).

Introducing on-demand small cells has the potential to several new advantages, in terms of reducing signaling overhead to reducing costs of network deployed small cell, as well as means for enhanced way of mobility management.

**IV. PERFORMANCE EVALUATION**

In this section, we present preliminary performance evaluation results to show the advantages of adopting the scenario of deploying mobile small cells based on C-RAN.

**A. SIMULATION SETUP**

We start by describing the deployment scenario used in our simulation setup. The simulation scenario is shown in Fig. 3. In the simulation, we adopt a HetNet OFDMA network with interference coordination between different cells by using C-RAN methodology through eNB of each cell. The simulated scenario represents 3 tier hexagonal cellular layout, which is composed of 19 eNBs with 3 sectors each (hence 57 sectors). Within each cell, one eNB exists along with multiple low-power small cells (either RRUs or UEs.
used as a mobile small cell). Each cell is divided into 3 sectors; each sector has 3 small cells (9 small cells per each hexagonal cell). eNB acts as the cloud controller to control all the RRUs under its coverage. We implement a wrap-around model to avoid border effects. We apply Monte Carlo iterative simulation method to evaluate the performance of our envisioned C-RAN based mobile small-cell scenarios by using Vienna LTE Simulator [14]–[16]. All relative simulation parameters are given in Table 1.

### B. PERFORMANCE EVALUATION

In this set of simulation results, we show the benefits that would be gained by deploying C-RAN based small cells (whether they are RRUs or mobile user devices). In the beginning, we show the effect of the small cell deployment on the variation of the quality of received service among users over the coverage of the mobile network. Additionally, the second half of the results elaborates the gains in throughput and spectral efficiency received by the mobile users; hence the increase in the average received quality of service (QoS).

Fig. 4 shows the variation of the region of interest (ROI) over the coverage of all the cells considered in the simulations. It can be clearly observed that the addition of mobile small cells within the coverage of the macro-cell increases the areas with good service. Most of the cell coverage receives good signal. This is further illustrated by the next figure.

Fig. 5 plots the Signal to Interference Noise Ratio (SINR) deviation over the network coverage. The figure illustrates how deploying small cell enhances the service over the whole area of the cellular network. The figure shows that the achieved SINR is in acceptable high level (dark red) all over most of the coverage of the network. It is clear that the effect of near-cell-edge service has been reduced to a very thin border line, which is almost negligible compared to the whole area of the cells. Even this issue can be resolved, by placing small cells exactly on the border between two macro-cell eNBs. This set of results clearly show the advantages gained by placing small cells (i.e. mobile small cells) within the coverage of macro-cells in reducing the variation in the QoS received by mobile users over the coverage area of

<table>
<thead>
<tr>
<th>TABLE 1. Simulation Parameters</th>
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<tr>
<td><strong>Parameter Name</strong></td>
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<tr>
<td>Simulation Mode</td>
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<tr>
<td>Technology</td>
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<tr>
<td>Number of Cells</td>
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<td>Inter-cell distance</td>
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<td>Number of sectors</td>
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<td>Log-normal Shadowing Model</td>
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<td>Fading Model</td>
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<tr>
<td>TTI</td>
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<tr>
<td>Reference Symbol overhead</td>
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<tr>
<td>CRS: 2 CRS Release-8 legacy overhead [19]</td>
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<tr>
<td>(DM-RS: Demodulation Reference Symbol)</td>
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<tr>
<td>CRS: Common Reference Symbol</td>
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<tr>
<td>RE stands for Reference Element</td>
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<tr>
<td>Link-to-system interfacing</td>
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<td>MCS types</td>
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<td>HARQ</td>
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<tr>
<td>Scheduler</td>
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<td>Total number of UEs</td>
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FIGURE 4. ROI variation over the area of mobile cells.

The second set of results shows the increase in received QoS. Fig. 6 presents the average spectral efficiency received by users. We compare the spectral efficiency when small cells are deployed according to our proposal (Fig. 6a) to that received in legacy deployment without small cell (Fig. 6b). From that comparison, it can easily be seen that by deploying small cell, the average received spectral efficiency of users is increased. It is shown that using small cell deployment 50% users would be receiving more than 3.5 bit/cu compared to only 0.7 bit/cu in case of deployment without small cells. This illustrates almost a 5 times enhancement in the average received spectral efficiency.

Finally, Fig. 7 presents the average throughput received by users in both deployments (with and without small cells). It is shown that the average throughput received when small cells are deployed (Fig. 7a) is higher compared to the average throughput received in legacy case without small cell deployment (Fig. 7b). It can be seen from the figures that 50% of users receive more than an average throughput of 12 Mbps compared to only 2 Mbps without using small cell deployment. The average throughput achieved is 14 Mb/s in the proposed scenario with small cell deployment, with a peak throughput of 28.87 Mbps.

The set of results presented above shows the advantages gained by deploying small cells within the coverage of macro-cells, as proposed by our innovative deployment scenario. The results illustrate how deploying small cells decrease the variation in the quality of received service over the coverage of the cellular networks; hence providing more uniform QoS among users independent on their location within the network. The results also emphasize the enhancement in the QoS received per user in terms of higher spectral efficiency and throughput.

In general, the simulation results confirm that small cell deployment enhances the QoS received by mobile users, no matter where their location is.

V. DEPLOYMENT ENHANCEMENT

Having shown the advantages gained from our proposed scenario (C-RAN based mobile small cells), we move another step forward and look into possible futuristic technology trends that can be added and further enhance the performance of the proposed C-RAN based mobile small cells.

Another dimension for enhancement can consider SONs. SON is considered as an indispensable technique for the
success of small cell networks. In order to enhance the capacity of small cell users, a small cell network should adopt an automatic self-organizing scheme that adapts transmit power and dynamically selects frequency, guaranteeing the performance of macrocell users. We hence propose a self-organizing scheme that dynamically selects frequency band according to an optimal FFR and adapts transmit power control for a future enhancement of our proposed solution.

VI. RESEARCH CHALLENGES

Our proposed solutions provide many advantages, as discussed above, including system capacity increase, higher data rates, more supported devices at low cost (no network planning nor deployment) and lower energy consumption (less network devices and shorter communication links); however, to fully exploit the advantages of such solutions, certain design issues and open research challenges have to be addressed. In this section, we list the foreseen open research challenges in each scenario defined in the previous section.

Basiclly, in the scenario of heterogeneous deployment of small-cells alongside macro-cells, current approaches are all still limited in terms of spectral efficiency and complexity. A general open question is how to effectively manage interference in multi-tier cellular environments that includes random deployment of small cells. In general, there is a need for a thorough investigation of the impact of inter-cell interference, when multiple small cells are randomly overlaid onto a sector of the macro-cell.

When C-RAN is considered for interference management in multi-tier infrastructure networks, we have identified several research questions that need to be answered:

- Despite that fact that interference can be substantially managed/reduced/mitigated through coordinated and cooperative resource management, this requires coordinated scheduling between small cells and the macro-cell. A coordinated approach also affects the complexity of the system, with a potential trade-off foreseen between the coordination set-size, complexity, and transmission power. How to attain this delicate trade-off while maximizing spectral efficiency needs to be determined [21].
- The fronthaul design is essential to the data connection speed of the small cell, especially for the sake of delivering very high speed to cell edge. Until now, optical and microwave point-to-point links have been viable options providing a reasonable trade-off between deployment cost and throughput. However, with the emergence of mmWave technology, we now have a new area to explore that has the potential to provide very high speeds by using multiple antenna technology per device. How can mmWave fronthaul segment be included, along with its feasibility with regards to deployment cost are open issues needs to be addressed.
- In practicality, C-RAN could provide an additional opportunity for energy efficiency, since coordination and cooperation of the baseband processing inside a cloud pool might save energy, especially if advances on green data centers are leveraged. How to deal with complete characterization of the energy consumed by the circuitry needed for C-RAN is an open question.
- The win-win accommodation of having many small cells or fewer macro cells given their very different power dissipations is also of a pivotal research challenge.

Considering on-demand mobile small cells (aka. mobile handsets used as small cells) is one of the main innovative contributions of this paper and is expected to provide many advantages in terms of increased capacity and data rates, energy efficiency, reduced cost, flexibility and reduced signaling overhead; however, such concept raises the most research challenges, namely:

- Interference management between randomly implemented on-demand small cells.
- Efficient node discovery mechanism [22].
Choice of mobile handsets to act as small cells will be a major research challenge. The criteria for choice could include - among others - handset capabilities, residual battery level, and mobility patterns [23].

- Security will become a major issue in such scenario. User data will be relayed through other users’ handsets, which will raise privacy issues. Additionally, authentication will become more complicated.

- Incentives algorithms will be required [24]. Handsets used as small cells will use their resources to serve other users. Some incentives will be required to encourage users to allow their handsets to be used as small cells.

It is worth noting here that the proposed solutions are promising in terms of increasing the capacity of the mobile networks, supporting more devices, decreasing energy consumption, all at reduced cost to the network operator (no network planning nor excessive deployment costs). These advantages are achievable with current technology trends; however, the open research challenges need to be answered, if the concept of low-cost energy-efficient on-demand mobile small cell is to achieve its anticipated full gains.

**VII. CONCLUSION**

Mobile traffic and the use of sophisticated broadband services, along with the anticipated increase in number of mobile devices are pushing the limit on current mobile standards. Incremental advances are not foreseen to meet the requirements of mobile networks by 2020; hence all research efforts are now directed towards 5G. This has made mobile operators reluctant to invest in new solutions. In this paper, we discuss a low-cost solution built on technologies that are widely accepted to continue to exist within the 5G paradigm. The solution builds on the vision of 3GPP small cells and goes beyond by exploiting mobile handsets to form on-demand small cells, where mobile devices are seen as a pool of additional network resources. The proposed solution also proposes using C-RAN architecture, which represents a technology foreseen to play part of the 5G paradigm. The paper also provides a vision for 5G paradigm, which shows how the solution can be adopted using current technology and continues to exist within 5G paradigm.

Simulation results show the performance enhancement of our proposed solution compared to macro-cell deployment without the adoption of the concept of on-demand mobile small cells. The envisioned scenarios provide improved capacity and throughput, higher data rates, better service variation over the coverage of the mobile network, at low costs for operators; The proposed solution does not require extensive network planning nor network elements deployment. Simulation results show increase in average throughput and spectrum efficiency up to 5 times. Despite the advantages, the scenario raises significant research challenges (e.g. mobile small cell coexistence, and mobility management), which are outlined in the paper.

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two Portuguese funded projects (SmartVision and Mobilia) in the area of networking coding and development of system level simulator for 5G wireless system. He has several years of experience in 3GPP radio systems research with experience in HSPA/LTE/LTE-A and strong track-record in relevant technology field, especially physical layer technologies, LTE cell planning and optimization, protocol stack, and system architecture. His research interests lie in the field of architectural enhancements to 3GPP networks (i.e., LTE-A user plane and control plane protocol stack, NAS, and EPC), 5G related technologies, green communications, cognitive radio, cooperative networking, radio resource management, cross-layer design, Backhaul/fronthaul, heterogeneous networks, M2M and D2D communication, and baseband digital signal processing. He has more than 60 publications in international conferences, journal papers, and book chapters. He is serving as a Vice Chair of the IEEE 5G Standardization. In 2012, he received the Alain Bensoussan Fellowship by the European Research Consortium for Informatics and Mathematics to pursue research in communication networks for one year at the VTT Technical Research Centre of Finland. He is also an Editor of three books and served as a Guest Editor for special issue in the IEEE Wireless Communications Magazine and the IEEE Communication Magazine. Recently, he is appointed as a Permanent Associate Technical Editor of the IEEE Communication Magazine, the IEEE Journal of IoT, and the Journal of Digital Communication and Network (Elsevier). He has been on the technical program committee of different IEEE conferences, including Globecom, ICC, and VTC, and chaired some of their symposia. He was the Workshop Chair in many conferences and recipient of the 2006 IITA Scholarship, South Korea.

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