Energy-Efficiency Analysis of Cloud Radio Access Network in Heterogeneous 5G Networks

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Abstract

5G is expected to bring unprecedented innovations in cellular networks, necessary to provide a clear step forward in terms of performance, but also in terms of management and efficiency. This paper addresses the concept of Cloud RAN planning from a quantitative perspective, by proposing a mathematical framework based on the stochastic geometry paradigm to analyse and compare the current 4G/LTE cellular architecture with the 5G Cloud RAN concept in terms of energy consumption in heterogeneous scenarios. Preliminary results, based on actual data from the city of Manchester, provide interesting insights to the potential advantages of Cloud RAN design in lowering energy consumption, and reveal the good potential of the proposed analytical approach.

Index Terms

5G, stochastic geometry, C-RAN, virtualization, energy efficiency.

I. Introduction

Fifth generation (5G) cellular networks are currently a hot topic in the design and research of next generation cellular networks. Indeed, 5G is expected to bring an unprecedented step forward in performance but also relevant changes in the overall network and management architectures.

The major challenges to enable to fulfil 5G requirements can be summarised as follows: (i) densification of base stations/access points; (ii) spectral versus energy efficiency trade-off; (iii) spectrum scarcity; (iv) software-defined, centrally-controlled, shared, virtualized architecture [1]. Densification of base stations (BSs) and heterogeneity in the radio access trunk represent the main challenges to support high throughput, proper frequency re-use and support for traffic hot-spots. Densification brings increase in complexity for managing the radio access network (RAN) as well as potential concerns related to energy consumption. Indeed, 5G is expected to incorporate several types of base stations, ranging from macro-cells (like in the case of LTE eNodeB) to femto and pico-cells, and each cell type is characterised by different features and energy consumption characteristics. Proper planning will be required to balance performance with energy efficiency in order to guarantee high performance and at the same time a sustainable and scalable solution.

Managing such a complex scenario will surely push the current architectures to the limit, and potentially require a change to overcome the lack of flexibility in reconfiguration and real-time adaptation of current cellular architectures. To achieve this goal, and also to support efficient sharing of infrastructure among several operators, virtualization and software-defined networking (SDN) paradigms are currently identified as proper solutions to provide a higher degree of control and to improve the allocation of resources (communication, processing, storage, etc.) based on the operating context and service requirements.

In this scenario, the concept of cloud radio access network, or Cloud RAN (C-RAN) [2], [3], was recently proposed to address issues indicated above as (i), (ii) and (iv). Basically, the idea behind Cloud RAN is to enable higher flexibility in management and configuration of the RAN section of a cellular network by detaching base-band processing functionalities from standard BSs/eNodeBs and moving them in convenient locations where shared processing facilities will be available. In this way, eNodeBs will become less complex and power hungry (in some cases as simple as remote radio heads - RRHs) and their detached processing functionalities will become virtualized network functions named virtual base-band units (v-BBUs). This allocation is expected to be more flexible and efficient as the position and processing power allocated to each v-BBU could be defined based on the current load of each RRH and the operating context. Moreover, the utilisation of pools of resources for v-BBU allocation will enable easy migration and provide cost-effective consolidation of co-located virtual entities.

To better understand the problem, Figure 1 provides some details about peak power consumption of cellular base stations in different cell configurations. As it is well-known, macro-cells are characterized by a high percentage of power consumption due to the Power Amplifier, therefore requiring efficient power adjustment or on-off functionalities to enable energy efficient operation. However, in the case of micro- or pico-cells, which could represent the actual densification scenario foreseen in 5G use cases as well as in heterogeneous cases, the percentage of power consumed for transmitting is almost equal to the power required for base-band processing operation. As a consequence, understanding in which situations it is useful to virtualize base-band processing, represents a central issue in studying efficient deployment of Cloud RAN solutions.

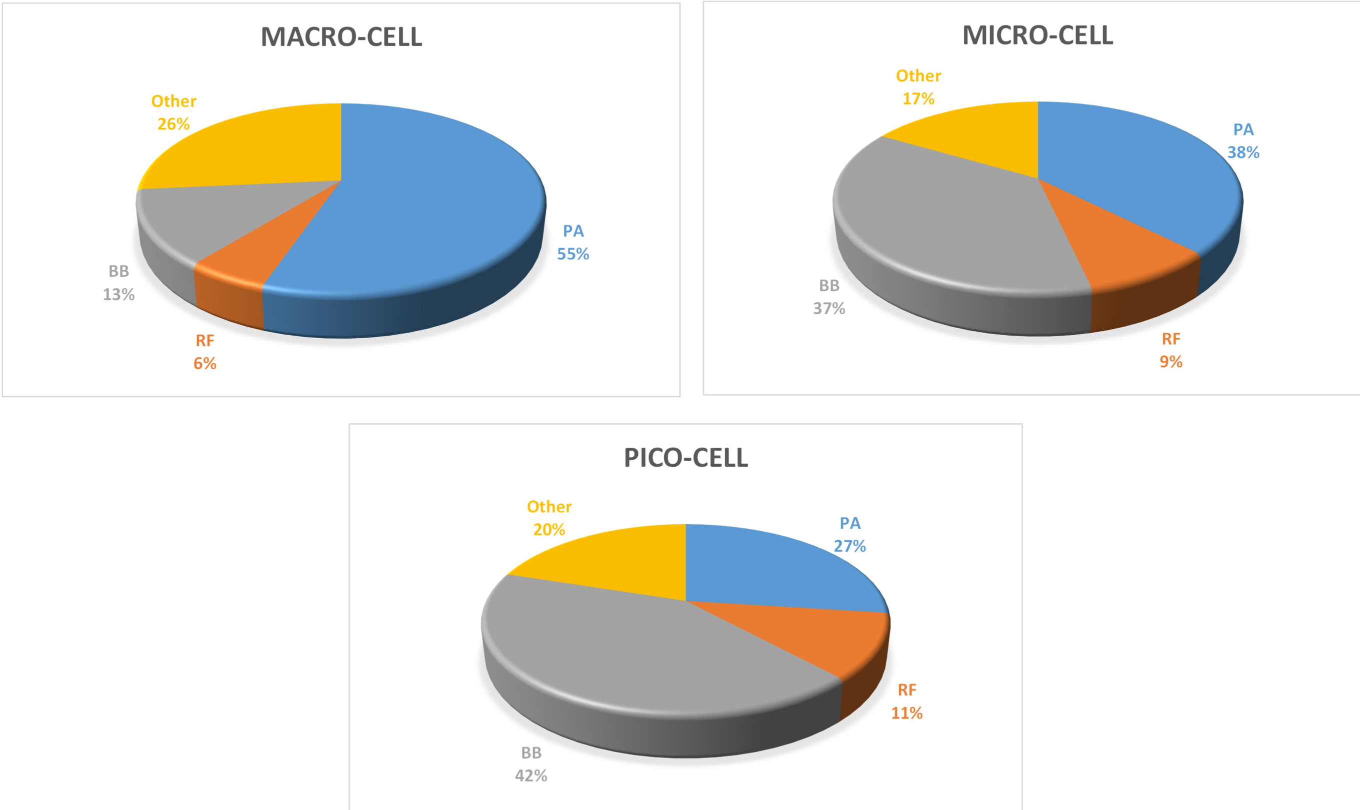

Fig. 1. Breakdown of Base Station power consumption in LTE, based on data from [4]. The blue slice refers to power amplifier (PA), the orange slice refers to radio frequency (RF), the grey slice refers to baseband (BB), and the yellow slice refers to other general sources of consumption.

Quantitative estimations of the performance of Cloud RAN and its effectiveness in terms of energy and costs have already been addressed in the literature. In 2015, reference [5] proposed a method to virtualize BBUs in order to minimise power consumption, by keeping computational complexity linear. Next, authors of [6] discussed the energy efficiency aspects and benefits of C-RAN to evolve efficiently current LTE infrastructure towards future 5G networks. The work in [7] modelled and evaluated the power consumption of SDN-based C-RAN to prove the potential reduction in energy efficiency due to the deployment of these recent technologies. Traffic-aware approach to C-RAN have been proposed by [8], which analysed the complexity of the approach and how to achieve energy optimisation towards green 5G networks. A quantitative analysis of the number of required v-BBUs in a 5G scenario was presented in [9]. Next, reference [10] studied the deployment cost and traffic requirements of v-BBU pools, focusing on processing capacity and latency. Moreover, it provided an approximation algorithm to solve this issue since the problem was defined as NP-hard. Next, the authors in [11] analysed the relationships and the impacts among distance between v-BBUs and RRHs, channel conditions and required processing power. An energy-efficient association scheme between v-BBUs and RRHs based on graph partitioning and rejoining was proposed by [12].

A general analysis of the above literature shows the necessity of a novel theoretical approach/model to guarantee flexibility and suitability in the characterisation of some aspects of future 5G networks. Especially, the previous works do not consider the heterogeneity of access networks (multi-tier scenario) and the influence of spatial distribution of BSs and mobile users.

In this sense, the paper aims at enabling a step forward in quantifying the potential of a Cloud RAN architecture for 5G, by defining a suitable analytical framework to study the existing trade-offs in terms of energy consumption, spatial distribution of BSs and users' coverage. To achieve this goal, while maintaining a sufficient degree of generalisation, the proposed framework is based on stochastic geometry, recently applied with success to the design of traditional radio access networks. Currently, to the best of authors' knowledge, this is the first article exploiting the capabilities of stochastic geometry and tessellation theory to study the energy consumption of C-RAN-based 5G heterogeneous cellular networks.

Figure 2 depicts the general theoretic method, this work proposes to estimate C-RAN energy consumption in different real scenarios. The first step is the analysis of input data from the scenario. The second step is the choice of the most suitable tools from stochastic geometry and tessellation theory to model the real characteristics. Side by side, there is the selection of a traffic model to describe the temporal behaviour of the load due to mobile users. The third step is the definition of a specific energy model, and the fourth is the numerical evaluation in terms of energy consumption.

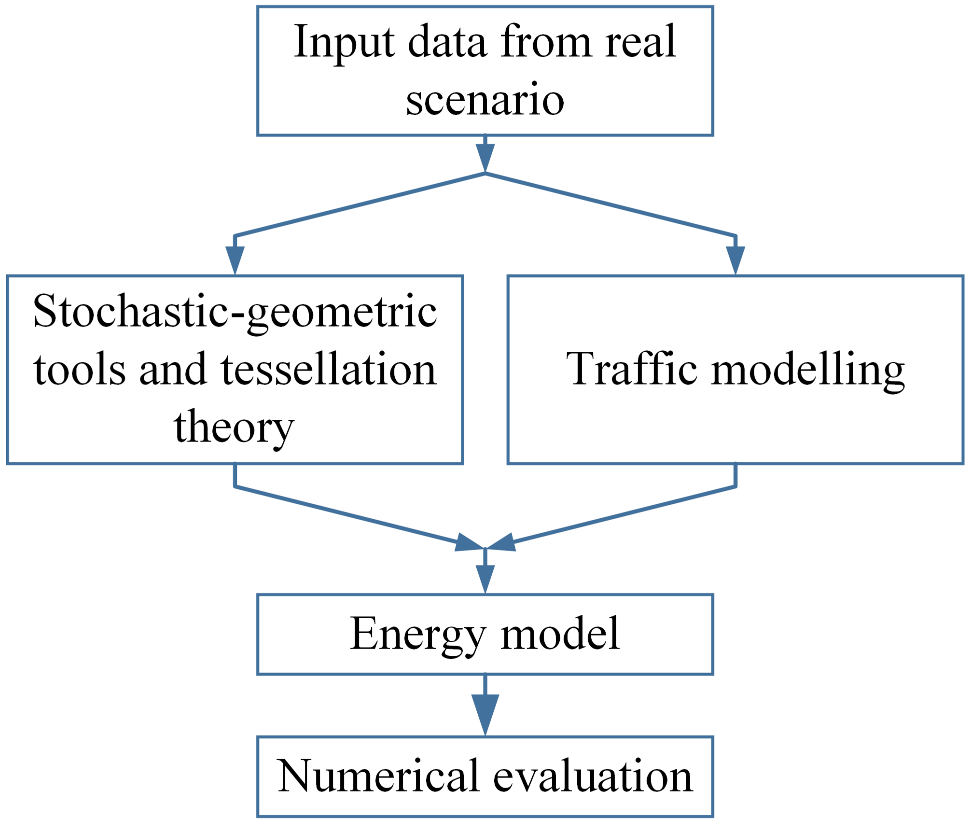

Fig. 2. Representation of the logic steps proposed by this article to model and to evaluate energy consumption of C-RAN-based heterogeneous future generation cellular networks.

Finally, the main points of innovation of the paper can be summarised as follows:

- Proposing a general analytical approach to study energy efficiency of Cloud RAN and virtualized cellular network infrastructures.
- Proposing a novel approach to analyse the variation in number of active v-BBUs and to analyse quantitatively energy efficiency in heterogeneous Cloud RAN scenarios. The required v-BBUs and the related energy consumption can be computed in closed form expressions.
- Providing a first quantitative comparison in terms of energy consumption between LTE/LTE-A Radio Access Infrastructure and 5G Cloud RAN in heterogeneous networks.

The structure of the paper is as follows: Section II discusses the usage of stochastic geometry as a suitable tool for studying heterogeneous cellular networks in presence of virtualization, while Section III introduces the proposed system model and the example scenario to be evaluated. Finally, Section IV provides some numerical results.

II. Why Stochastic Geometry for Virtualization?

Heterogeneous ultra-dense cellular networks constitute an enabling architecture for achieving the disruptive capabilities that 5G of cellular networks is expected to provide. Modelling, simulating, analysing and optimising such networks is, however, a non-trivial problem. This is due to the large number of BSs that are expected to be deployed and their dissimilar characteristics, which encompass deployment density, transmit power, access technology, etc. In addition, future cellular networks will rely on network resource sharing and network function virtualisation, as discussed and motivated in the previous section.

Motivated by these considerations, several researchers are investigating different options for modelling, simulating, mathematically analysing and optimising next generation cellular networks. This is the reason why, in the literature to date, the efficiency of joint radio access network, spectrum sharing, and network function virtualisation has been evaluated through extensive numerical simulations.

The general consensus is, in fact, that the methods used in the past for modelling cellular networks, e.g., the hexagonal grid-based model, are not sufficiently scalable and flexible for taking the ultra-dense and irregular deployments of emerging 'virtualized' cellular topologies into account, and for providing general guidelines for system design and optimisation.

Recently, however, a new approach for overcoming these limitations has been proposed. It is based on the theory of point processes (PP) and leverage tools from stochastic geometry for system-level modelling, performance evaluation and optimisation of future cellular networks. Unlike its intractable grid-based counterpart, the locations of cellular BSs, access points, RRH, etc. are not assumed to be regularly deployed, but are randomly distributed according to a PP. This approach, due to its mathematical flexibility for modelling heterogeneous ultra-dense cellular deployments, is today considered the most adequate for designing and optimising future networks. Recent results on stochastic geometry modelling of future networks with and without network resource sharing and their experimental validation are available in [13], [14].

Furthermore, the most recent works exploit random tessellation theory in order to model cellular networks and coverage. Initially, Voronoi diagrams [15] have been applied to study the geometric properties of single-tier cellular networks [16]. Nevertheless, the need to study more complex scenarios towards heterogeneity of 5G future cellular networks, required the deployment of more sophisticated tessellations such as multiplicatively-weighted Voronoi (MWV) tessellation [17]: in fact, multi-tier cellular networks have access points of different transmission power, which implies a different kind of coverage regions per each tier.

The three elements that characterise a Voronoi diagram are: generators, edges and vertices. First, the *generators* are the initial set of points distributed on the plane according to a PP. Second, the *edges* are the lines on the space that are equidistant between two generator points. Third, the *vertices* are are points that belongs to the edges and are equidistant from three or more generator points. In some scenarios, it can be useful to assign weights to generators instead of them of the same uniform weight. In particular, the assignment of different weights changes the graphic characteristics of the edges, becoming circular arcs and not straight lines any more.

Network function virtualization and Cloud RAN are areas of research that have been strongly investigated via software simulations, testbeds and real initial implementations. However, there is a significant lack of analytical models to approach to these fields. Hence, the main objective should be to provide theoretical means in order to dimension parameters and to design characteristics to be then developed by software and testbeds. The power of stochastic-geometric models, revealed in the study of rapidly changing environments such as wireless networks, is highly promising to make this field of mathematics an important mean in the analysis of virtualized environments. In fact, both wireless and virtualized networks present probabilistic changing scenarios, which could gain by applying random-geometric objects and point process theory.

III. System Model

The reference scenario considered in the paper is a two-tier 4G/LTE network. The cellular network is a two-tier network, which comprises micro and pico cells. The micro and pico BSs are distributed on an Euclidean plane $\mathbb{R}^2$ according to two-dimensional homogeneous Poisson point processes (PPP) Φ_{BS_m} and Φ_{BS_p} of intensity λ_{BS_m} and λ_{BS_p}.

Mobile terminals (MTs) are also distributed according to a homogeneous PPP Φ_{MT} of intensity λ_{MT} [13]. The PPPs Φ_{BS_m}, Φ_{BS_p} and Φ_{MT} are assumed to be independent. In the network, each MT is associated to the nearest BS, and it is assumed that each MT can be served in a single resource block at a given time. These hypotheses rely on the results [14], which prove the correctness of PPPs to model the real scenario of Manchester. That is subsequently used in the next section for numerical evaluation.

As explained in Section II, given the different transmit power (and as a consequence range) of the tiers, the coverage cannot be modelled using a standard Voronoi tessellation, since the points of Φ_{BS_m} and Φ_{BS_p} have different weights (i.e. different transmission power). Hence, the scenario is modelled by a Multiplicatively-Weighted Voronoi tessellation.

In order to model and to evaluate this heterogeneous scenario, we exploit some of the results described in [17]. Let's consider the case, in which an MT can connect to any BS without restrictions. That can represent the real case in which customers can connect to any BS of their operator in a geographic region. The *average fraction of users served by j-th tier* [17] can be expressed as

$$N_j = \frac{\lambda_j {P_j}^{2/\alpha} {\theta_j}^{2/\alpha}}{\sum_{i=1}^{2} \lambda_i {P_i}^{2/\alpha} {\theta_i}^{2/\alpha}} \quad (1)$$

where P_i is the transmission power of the i-th tier, θ_i is the signal-to-interference-plus-noise ration (SINR) threshold and α is the path loss exponent. As a consequence, each BS of the j-th tier has an average load of N_j/λ_j.

Furthermore, the scenario can either include 4G/LTE BBUs co-located with each BS or take advantage of Cloud RAN with v-BBUs distributed according to a PPP Φ_{vBBU}, with intensity λ_{vBBU}. For the purpose of providing a realistic figure of the computational power of BBUs and vBBUs, the technical specifications for the Huawei model eBBU530 are used in the rest of the paper. Nevertheless, as the reader will notice, other values for the characterization of the BBUs can be easily included in the proposed analysis.

As the distance of v-BBUs from the served BSs might increase the communications latency, the assumption is made that BSs are connected to the nearest v-BBUs. This implies that in the considered model the v-BBUs serves the BSs that are placed in their respective Voronoi cell.

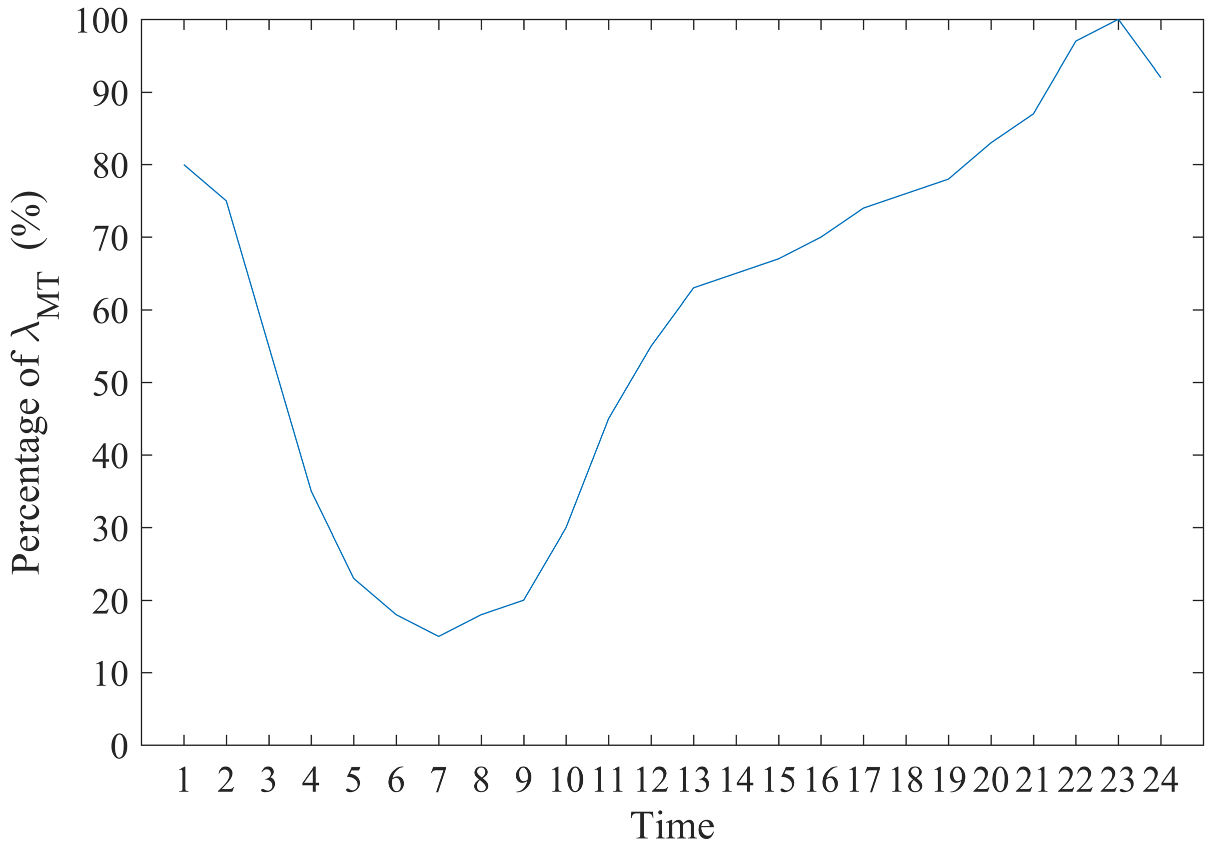

Fig. 3. Average variation of intensity of active mobile terminals (λ_{MT}) according to the hours of the day.

The final scenario is the superposition of a Voronoi tessellation generated by Φ_{vBBU}, and of a MWV tessellation generated by the union Φ_{BS} of Φ_{BS_m} and Φ_{BS_p}.

By considering the results in [13], under the above assumptions it is possible to derive the random variable N_{BS}, which denotes the number of BSs in the Voronoi cell associated to a randomly chosen v-BBU. The probability mass function (pmf) of N_{BS} is

$$P\left[N_{BS}=n\right]=\frac{3.5^{3.5}\Gamma\left(n+3.5\right)\left(\lambda_{BS}/\lambda_{vBBU}\right)^{n}}{\Gamma\left(3.5\right)n!\left(\lambda_{BS}/\lambda_{vBBU}+3.5\right)^{n+3.5}} \quad (2)$$

where $\Gamma\left(x\right)$ represents the gamma function.

In order to provide a fair comparison, the considered system model associates to all BBUs and v-BBUs the same processing capabilities. In particular, we define the processing capability of a BBU/v-BBU is defined in this paper as the maximum number of connections of MTs that a v-BBU can support (η).

By using the statistics provided in [4], it is possible to obtain the average percentage of active users connected to the cellular network in a dense urban scenario.

The urban scenario considered in this article is based on the available data from the city of Manchester. Figure 3 depicts the average variation of density of active MTs according to the hours of the day (i.e. the hourly variation of λ_{MT}).

The paper uses the generic energy model described in [18] for the operating power of Base Stations. Thus, the power consumption of a BS can be expressed for 4G/LTE as

$$p_{OP}(t)=(1-\delta)\rho(t)P_{OP}+\delta P_{OP} \quad (3)$$

and for 5G with C-RAN as

$$p_{OP}(t)=(1-\delta)[\rho_1(t)P_{Tx}+\rho_2(t)P_{BBU}]+\delta P_{OP} \quad (4)$$

P_{OP} represents the maximum operating power of a BS when fully (100%) utilised. In the proposed model, we consider P_{OP} to have two components: P_{Tx} and P_{BBU}, which are the transmission power and the power consumption of the BBU,

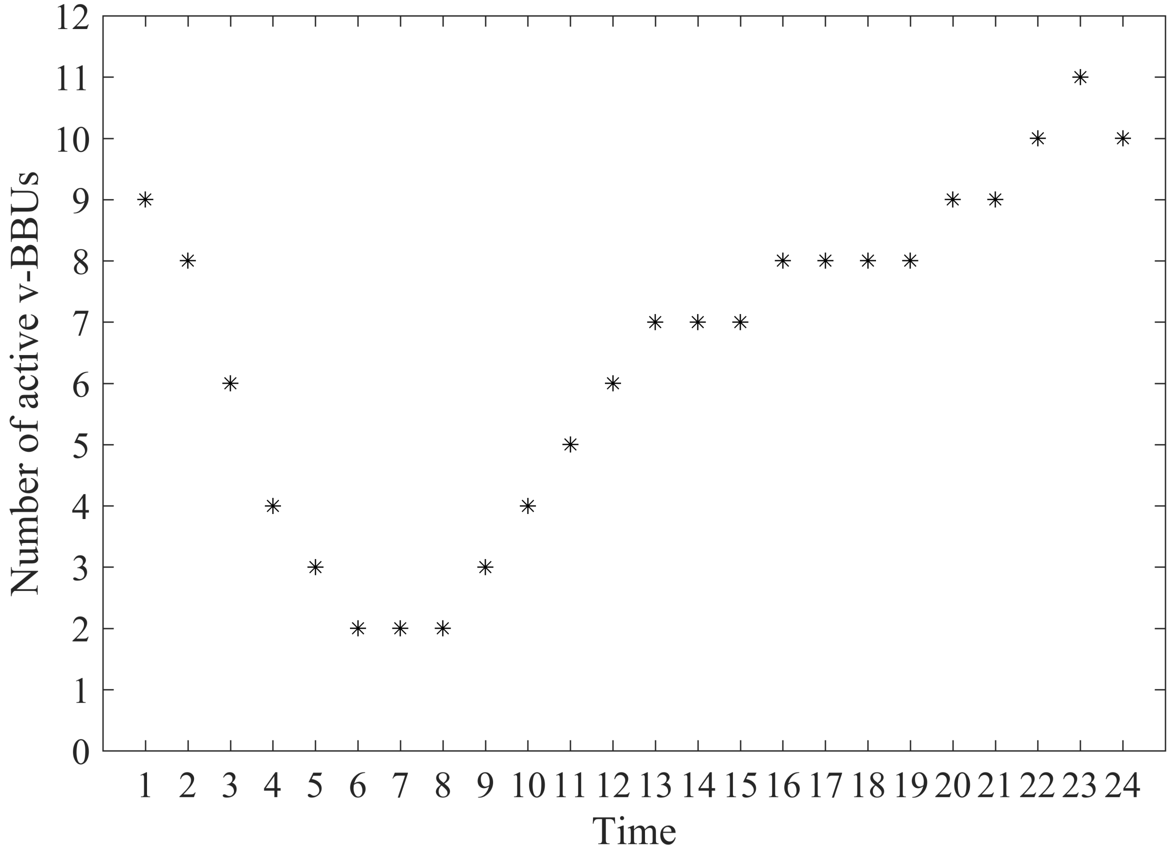

Fig. 4. Number of active v-BBUs during the time of the day.

respectively. Other components such as air conditioning or other losses due to power conversion are neglected in this analysis. As a consequence, the maximum operating power can be expressed in the form: $P_{OP} = P_{Tx} + P_{BBU}$, where $\rho(t)$, $\rho_1(t)$ and $\rho_2(t)$ are parameters that describe the variation of load during time in percentage. Clearly, if a BS that is not transmitting: $P_{Tx} = P_{BBU} = 0$.

Based on the parameter δ, it is possible to study the energy performance of 4G/LTE and 5G with C-RAN using three different power consumption models: (i) *constant energy consumption* (CEC), with $\delta = 1$, (ii) fully energy proportional (FEP), with $\delta = 0$, and (iii) non-energy proportional (NEP), with $0 < \delta < 1$. The first model represents BSs with constant energy consumption, without any influence of traffic variation. The second model describes an adaptive BS, where the energy consumption of BSs varies according to traffic load in a proportional manner. This model could represent a future scenario where BS power consumption is proportional to the offered load, and it is zero in absence of load. Finally, the third model combines the effect of constant energy consumption together with a term dependent on the traffic variation, therefore it can be used to represent the current BS power consumption pattern - where power consumption is not zero even in absence of load.

IV. Results and Discussions

The objective of this section is to estimate the energy gain obtained by applying C-RAN and virtualization to improve current 4G/LTE cellular networks. In order to do that, we first calculate the minimum average value of v-BBUs, which are needed to support the corresponding computational load due to MTs. The simulation of the modelled scenarios is performed in the Matlab environment.

Based on the statistics for the city of Manchester provided by Vodafone BSs from [14], we can set $\lambda_{BS_m} = 13$ BS/km^2 and $\lambda_{BS_p} = 39$ BS/km^2. In particular, we consider the density of pico cells λ_{BS} being three times higher than the one of micro cells. Regarding the density of MTs, a reference value of $\lambda_{MT} = 500$ is used.

The analysis based on stochastic geometry uses the expected values of $N_{MT}$and the pmf of expression (2), respectively, to calculate the average load of each tier and BS of each tier and compute the expected number of BS per v-BBU, in order to evaluate the minimum value of active v-BBUs the network requires. Figure 4 represents the minimum number of v-BBUs

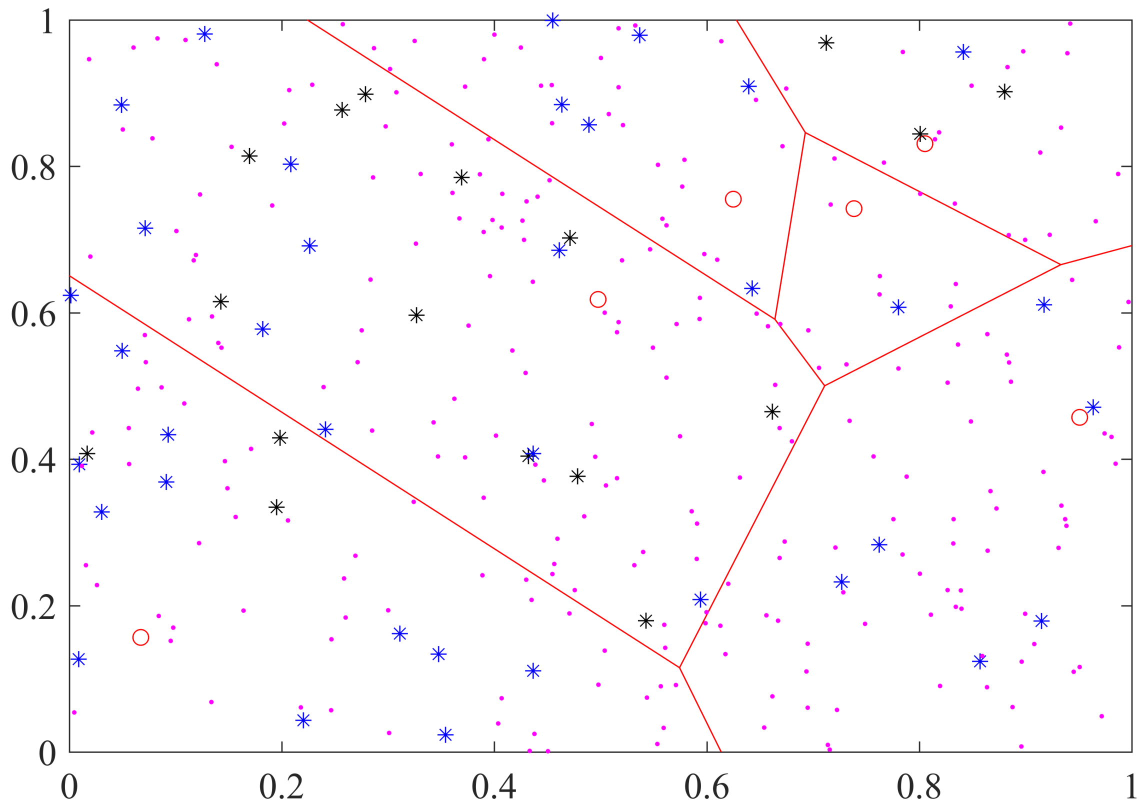

Fig. 5. Representation of Voronoi tessellation generated by homogeneous Poisson point process of v-BBUs. The v-BBUs are the red circles, the micro and pico access points are respectively the black and blue stars, and the mobile terminals are the magenta points. The snapshot shows the situation of the scenario at noon.

required by the two-tier scenario of Manchester with micro and pico cells, versus the hours of the day. The transmission power considered for the tiers is 6.3 W and 0.13 W for micro BSs and pico BSs respectively. In parallel, a snapshot of the scenario at noon is given in figure 5. The v-BBUs are considered distributed on the region according to a homogeneous PPP, and the respective Voronoi tessellation uses this point process as generator.

Regarding expression (1), we set path loss exponents at $\alpha = 4$ and $\alpha = 2$ [19] respectively for micro and pico cells, and SINR threshold at $\beta = 16$ [20] (i.e. good quality for LTE specifications).

Figure 6 compares the energy consumption of current 4G/LTE cellular networks with a C-RAN based cellular network. The evaluation considers the three energy models described in the previous section: CEC, FEP and NEP (with $\delta = 1/2$). If the Base Stations use always constant power regardless of the traffic variation, clearly both network paradigms achieve the maximum power consumption, which remains constant during the day. In this case, the energy gain of applying C-RAN is around 16%. By using an NEP energy model (which is best suited by today's BSs), the energy consumption decreases in case of low offered load, and the corresponding energy gain of C-RAN varies between 16% and 18%. Finally, by using an FEP energy model (which might represent a future scenario where BS hardware is more energy efficient than today), the energy consumption of the networks is further improved, and the energy gain of C-RAN changes between 17% and 20%.

V. Conclusions

Virtualization and cloud computing are becoming a significant aspect of next generation 5G cellular networks. Especially, C-RAN is the new technology that will enable the virtualization of the processing at BBUs in order to centralise it at the core network.

A preliminary study of energy efficiency of C-RAN in single-tier cellular networks was presented by the authors in [21]. Nevertheless, that work was also using a simpler power model. This article has come to enhance significantly the previous initial work [21], by facing the problem of identifying a more suitable model for analysing power consumption of C-RAN and current 4G/LTE RAN with stochastic geometry in multi-tier cellular networks. Particularly, this model enables to estimate

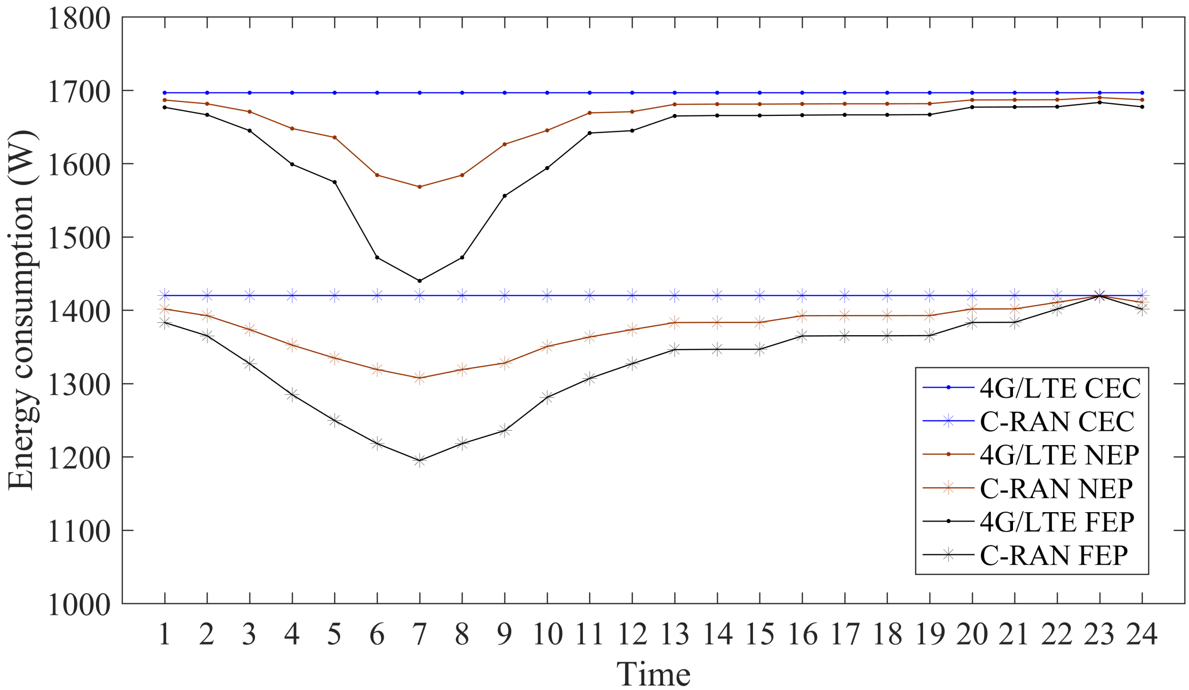

Fig. 6. Comparison of total energy consumption of 4G/LTE and C-RAN scenarios according to the hours of the day. For both technologies, the performance has been calculated in case of access points that are constant energy consumption (CEC), fully energy proportional (FEP), and non-energy proportional (NEP), with $\delta = 1/2$. The values take into account the consumption due to transmission and to BBUs/v-BBUs.

relatively accurate average energy consumption and average energy gain of 5G C-RAN in respect of current 4G/LTE technology in heterogeneous cellular scenarios. Results based on actual data provide validation of the proposed methodology. These results claim the deployment of C-RAN in Manchester can provide an average energy gain between 16% and 20%, depending on the considered energy model.

Acknowledgement

This work has been partially funded by NATO Science for Peace and Security (SPS) Programme, in the framework of the project SPS G5428 ”Dynamic Architecture based on UAVs Monitoring for Border Security and Safety”.

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