

Analyses of User Density Impact on Energy-efficiency Metrics in 5G Networks

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Abstract—As the number of fixed and mobile users increases constantly, the data traffic volumes increase accordingly, presenting a challenge for fifth-generation (5G) mobile networks to accommodate those high demands. Also, different demography classes which represent various expected user densities with different expected data rates, impose practical deployment challenges for 5G mobile networks. In such areas with diverse demography classes, the various number of 5G base stations (BSs) differing in size and capacity must be deployed accordingly. This directly affects the energy requirements of the 5G mobile network, and consequently the energy-efficiency (EE). In this paper, we calculate and compare standardised EE Key Performance Indicator (KPI) metric for the radio part of the simulated 5G mobile network. The analysis of the EE is conducted over four different demography class areas (indoor hotspot, dense urban, urban and rural), and for standardised data capacity EE KPI metric (bit/J). To present the impact of different 5G BS allocation strategies on the EE of the network for each demography class area, three different operation and installation strategies have been introduced. The analysis shows that the EE metric is significantly affected by different demography class areas, as well as by different operation and installation strategies of the 5G mobile network.

Keywords—energy-efficient, 5G, KPI, green, metric, network, base station, density, demography, mobile, users, traffic, cellular

I. INTRODUCTION

The energy-efficiency (EE) of mobile communication networks is becoming one of the key concerns as cellular networks advance in the number of served users and offered data speeds and capacities. With each new generation of mobile networks, energy demands are increasing, which is a result of the new requirements that are caused by the increased number of users and data traffic volumes. According to Ericsson mobility report [1], total global mobile data traffic reached about 33 EB per month by the end of 2019, and is estimated to reach 164 EB per month in 2025. Dominant mobile access technology during that period will be the fourth generation (4G) long term evolution (LTE) technology, and by 2025, it is predicted that 5G mobile networks will carry about 45% of total mobile data traffic. Increased demands for network capacity, throughput and coverage are mostly the result of global trends of high growth in the number of smartphone users. This growth is followed by increased usage of data-intensive content and an increased number of massive Internet of Things (IoT) connections where a vast number of devices will be able to communicate without human interaction. As the world is going towards ubiquitous networking, with emerging concepts of smart cities, smart homes, industry 4.0, self-driving cars, etc., it has become a

necessity to ensure high network availability, reliability, and EE.

Fifth-generation (5G) mobile network is expected to satisfy such high demands fulfilling the International Telecommunication Union (ITU) requirements for International Mobile Telecommunications-2020 (IMT-2020) systems [2], which are grouped under three categories: enhanced mobile broadband (eMBB) to satisfy high throughput and capacity demands, massive machine-type communications (mMTC) to satisfy an increasing number of machine to machine (M2M) communications, and ultra-reliable and low latency communications (URLLC) to ensure high reliability and low latency of real-time and critical communications. To meet such requirements, 5G mobile network is deployed as a heterogeneous network (HetNet) that encompasses macrocells for wide outdoor coverage, and small cells (microcells, picocells, femtocells) for indoor or outdoor coverage of the small geographical area with high throughput demands.

Because of the differences among requirements for various demography class areas in terms of user densities and data traffic volumes, a different 5G radio part of the network architecture for areas with different demography classes is required. Differences are primarily reflected in a number and type of BSs, which will ultimately have an impact on the EE of a 5G network. With an increase in the number of 5G macro and small BSs that are needed in practical cellular network installations, the energy consumption of the 5G networks will contribute to an increase of overall cellular network energy consumption of telecom operators (TOs). Therefore, an approach based only on maximizing the number of BSs gives the contribution to the increase in network coverage, capacity and user throughput, while neglecting EE of the whole network presents an economic, and as well, an environmental issue. As a result, EE became one of the Key Performance Indicators (KPIs) for 5G networks that is relevant during network life cycle phases.

Recently, different standardisation organizations such as European Telecommunications Standards Institute (ETSI) [3], International Telecommunication Union – Telecommunications Standardisation Sector (ITU-T) [4] and 3rd Generation Partnership Project (3GPP) [5], have defined through their standards and recommendations equal EE KPI metrics. Defined EE KPIs are seen as a means for providing TOs an insight in an EE of a network, which can ultimately help them during the planning and implementation phase, as well as during the operational phase of a cellular network. One of standardised KPIs is the data EE metric (bit/J), which takes into account two fundamental 5G network parameters which are: energy consumption and data volume.

TABLE I. BASE STATION REFERENCE PARAMETERS

Base station type	Spectral efficiency (bit/s/Hz/cell)	Channel bandwidth (MHz)	Number of sectors (cells)	BS capacity (Gbit/s)	Power consumption in sleep mode (W)	Power consumption in active mode (W)
5G macro	10	100	3	3	/	2000
5G small	6	800	1	4.8	5	50

Due to the 5G network deployment challenges which TOs will experience in areas with the various demography classes, in this paper we analyzed the impact of different demography classes (indoor hotspot, dense urban, urban and rural) on data EE metric. The analysis is based on three different 5G BS implementation approaches, and it is dedicated to deducing how different 5G BS deployment strategies affect the data EE of the 5G network. In this paper, the data EE metric is calculated and compared for three different implementation and deployment scenarios, showing a significant impact of user's density and the 5G BS deployment configurations on data EE of a cellular network.

The rest of the paper is organised as follows: a related literature overview of previous research activities on the cellular networks EE metrics is presented in Section 2. In Section 3, a standardised data EE metric for 5G networks is explained. For the purpose of network EE analysis, we present our simulation scenario of the tested 5G network in Section 4. Obtained data EE metrics for three different implementation scenarios are compared and discussed in Section 5. Finally, in Section 6, some concluding observations are given.

II. RELATED WORK

During the last decade, significant progress has been made in the academic and industry community regarding awareness related to the necessity of improving the EE of the radio part of the mobile access networks. Our initial work [6] analyses the EE metrics of the second generation (2G), third-generation (3G), and 4G macro BS sites in urban demography areas. It is shown that macro BSs transmit (Tx) power and inter-site distance have a notable impact on the area power consumption and bit-per-Joule EE metrics of a network. In [7], the authors have shown that an increase in power consumption caused by dense small cell deployment can be mitigated by using BS sleep mode strategies. Survey paper [8] provided solutions for increasing EE of mobile networks, that are grouped under four categories which are: resource allocation for maximizing the amount of information sent per Joule of energy, network planning and deployment for increasing the coverage area per consumed energy, energy harvesting and usage of renewable and clean energy sources for enlarging self-sustainability of the network, and specific hardware enhancements for improvement of TOs equipment EE in the radio part of the network.

Furthermore, in [9] authors have shown that switching from legacy LTE deployments to 5G radio access network (RAN) can reduce overall power consumption by 70%. The work presented in [10] confirmed that in heterogeneous cellular network deployments, using small BSs in combination with dynamic allocation of macro BSs transmit (Tx) power contributes to the increase of area and bit-per-Joule EE metrics. In [11], we have shown an impact that

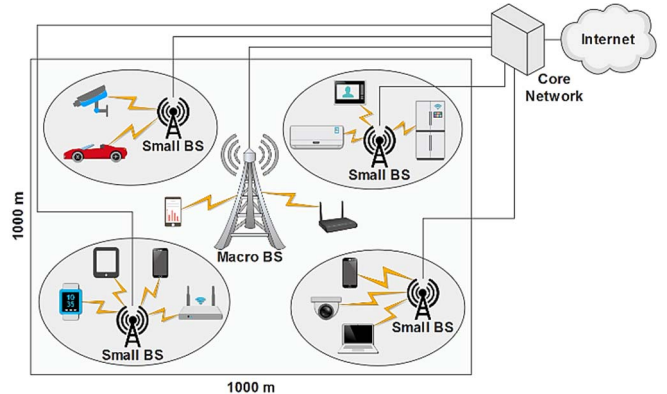


Fig. 1. Simulation model of a 5G HetNet

various HetNet deployments have on the power-per-unit area and energy-per-bit and unit area, with respect to Tx power and BSs inter-site distance adaptations. In paper [12], the authors presented an analytical framework for achieving high EE of 5G network, which is based on small cell densification using massive multiple-input multiple-output (MIMO) technology.

Authors in [13] develop a cost model for the optimal energy utilization of the small BSs in Hetnets, through the implementation of versatile approaches for sharing small BSs energy cost. In [14], authors extend results with a new concept for improving EE of Hetnets which is based on TOs bidding for small BSs resources instead of constantly exploiting the maximal capacity of small BSs. The proposed multiobjective framework is shown to be cost-effective and energy-efficient for the scheduling of small BSs resources. Additionally, in [15] is shown that possible solution for reducing energy costs of Hetnets can be realized through the implementation of small BSs having power supply from renewable sources.

However, previous research did not take into account the impact on Hetnets EE of the constant increase of small BSs number, caused by ascending user demands for higher capacity and data rates. To the best of our knowledge, the analysis considering how different user densities affect standardised data EE metric has not yet been provided. Hence, this work aims to give insights on how the different user densities in different areas having versatile demography classes, affect standardised data EE metric. Ultimately, TOs can use the outcomes of the analysis for the development of the practical installation strategies of energy-efficient 5G mobile networks in areas with different population densities.

III. STANDARDISED ENERGY-EFFICIENCY METRIC

Metrics and methods used to measure EE of 5G mobile radio access network (RAN) have been defined in ETSI standard (ES) 203 228 [3]. The standard defines equipment for EE evaluation which includes BSs, BS site equipment,

TABLE II. REFERENCE PARAMETERS FOR VARIOUS DEMOGRAPHY AREAS

Demography class	Downlink experienced data rate (Mbit/s)	Uplink experienced data rate (Mbit/s)	Maximal user's density (/km ²)	User's activity factor (%)	Area traffic demand (DV) for 80% user activity (Tbit/s/km ²)
Indoor hotspot	1,000	500	250,000	10 - 100	45.33
Dense urban	300	50	25,000	10 - 100	7
Urban	50	25	10,000	10 - 100	0.6
Rural	50	25	600	10 - 100	0.036

TABLE III. DESCRIPTION OF DIFFERENT DEPLOYMENT AND OPERATION SCENARIOS

Name of scenario	Scenario 1	Scenario 2	Scenario 3
Description of the scenario	Variable number of small BSs in active mode	Maximum number of small BSs in sleep mode	All small BSs constantly in active mode
Number of installed small BS during time	Variable	Constant	Constant
Number of active small BSs during time	Constant	Variable	Constant
Implementation of small BSs sleep-mode	No	Yes	No

equipment for backhaul communications and BSs radio controllers. Since the measurement of the test parameters for the complete TOs network is not feasible in most cases, the complete radio part of the TOs network is split into limited size sub-networks for the purpose of the EE assessment. In this work, reference 5G HetNet sub-network is used for EE evaluation. An analysis is restricted for the coverage area of one square kilometer, and for simplicity, only BSs in the radio part of the TOs mobile access network is taken into consideration (Fig. 1).

Also, for the EE assessment of TOs RANs, a set of parameters presented in Table I have been used in the analyses [3]. To calculate the data EE metric, energy consumption (EC) and data volume (DV) test parameters prescribed by ETSI are used in this work. Furthermore, the ETSI standard in [3] defines various sub-network demography classes, which are based on the population density of the specific demography area. In the analysis presented in this paper, areas composed of dense urban, urban and rural demography classes have been considered. Additionally, analyses are further extended for one specific demography class which will be particularly present in practical implementations. This demography class is an indoor hotspot area, for which parameters related to the user and data volume densities used in the analyses are defined in ETSI TS 122 261 [16] standard.

For the purpose of the EE analysis presented in this paper, only data EE KPI metric defined by ETSI ES 203 228, 3GPP, and ITU-T standards is used. Data based EE KPI metric expresses TOs RAN data energy efficiency ($EE_{MN,DV}$) as the ratio between data volume (DV_{MN}) and the energy consumption (EC_{MN}) of the RAN:

$$EE_{MN,DV} = \frac{DV_{MN}}{EC_{MN}} \text{ [bit/J]}. \quad (1)$$

DV_{MN} in relation (1) is defined as overall data volume delivered by the MNs equipment over the measurement period T . DV_{MN} includes packet and circuit-switched data volumes for downlink (DL) and uplink (UL) communication. The EC_{MN} in relation (1) is defined as the sum of the energy consumption of all TOs BSs over the same period T . In our analyses, this data EE KPI metric represents the overall data amount that can be reliably transmitted per Joule of BSs

consumed energy. In the next section, we present simulation scenarios for data EE analysis of the network under investigation, using described standardised data EE KPI metric.

IV. SIMULATION SCENARIOS

The simulation model of 5G HetNet under investigation is illustrated in Fig. 1. The reference coverage area of one square kilometer containing macro and small BSs is selected for data EE KPI metric calculation (Fig.1). Macro BSs are randomly allocated for ensuring full area signal coverage. Additionally, small BSs are located for providing capacity in micro-locations characterized by high data traffic (hotspots). Although real-world 5G HetNet implementations will be deployed using various types of small BSs (micro, pico or femto), for simplicity and to achieve generality, only one type of small BS is used in the analyses. Reference parameters that are used in the EE analysis of simulated 5G sub-network are presented in Table I [17]. To further simplify analyses, wireless local area network (WLAN) offloading has been neglected, and it is assumed that device-to-device relaying is carried over existing BSs in the simulated 5G network.

Four different demography classes are considered for an EE assessment. Demography class parameters in terms of DV and user densities are selected for analyses according to prescribed in ETSI TS 122 261 [16] standard (Table II). Parameters for sub-network demography classes shown in Table II represent different maximal user densities per square kilometer with a different DL/UL expected data rates. An area traffic demand presented in Table II, which is used as a DV capacity parameter for EE calculation, represents a total DL and UL communication for the area of the specific demography class. The impact of different user densities in different demography classes on data EE KPI metric, have been modeled using user's activity factor ranging from 10% to 100% of a maximal user density in the observed demography class. Hence, the user's activity factor is modeled as the number of active users in some moment per maximal estimated user's density in a specific demography area (Table II).

Furthermore, three different simulation scenarios have

been selected for the analyses. Depending on the demand for data capacity in each simulation scenario, different small 5G BS deployment approaches are considered. Small BS scheduling scenarios are modeled for the upcoming period of 5-10 years, in which the rapid growth of mobile data users must be accommodated.

Scenario 1 is based on a variable number of small BSs constantly working in active mode (Table III). In this scenario, the installation of new small BSs is gradual, and it is based on adopting a number of installed BSs according to the future needs for traffic capacity. Deployment of the new small BSs is based on DV requirements projected over a period of 5-10 years in which, TOs have to continuously respond to an increase in the number of users and corresponding DVs. Hence, the user's activity as an input parameter for the analyses is not related in time on a daily basis, which is characterized by data traffic variations in different periods of a day or day in a week. Instead, analyses take into account the general trend of increase in user's activity, which is a consequence of the global increase of TOs subscriber base during upcoming years and an increase in user's demand for higher data rates.

In Scenario 2, the maximal number of small BSs is assumed to be initially installed in the analysed area (Table III). The allocation of small BSs is based on satisfying the DV needs in the following time period of 5-10 years (as previously defined for Scenario 1). However, in Scenario 2, small BSs that are not needed for satisfying DV transfer are put into sleep mode and those BSs are activated as the data traffic demand increases in a particular area. Therefore, at any given moment, the maximal number of small BSs operates in the sleep mode. This Scenario 2 simulates an approach in which TOs need to adapt small BS activity according to DV variations. To be in line with state-of-the-art approaches based on putting in sleep mode small BSs during the periods of user's data traffic absence, small BSs instantaneous power consumption in sleep mode is set to 10% of the maximal power consumption in active mode (Table I).

In Scenario 3, unlike the 2nd Scenario, it is assumed that all installed small BSs are in active mode operating at maximum Tx power and consequently consuming maximal energy (Table III). The maximal number of small BSs is installed in the analysed area in order to accommodate capacity demand for the future time period (of 5-10 years) for the observed demography class (as previously defined for Scenario 1). Scenario 3 represents a dominating legacy approach which is less preferable from the EE standpoint, however, it is analyzed in this work to determine how the traditional BS allocation approach affects the EE of a TOs network.

Also, all scenarios are based on principle according to which, the amount of traffic that exceeds the capacity of macro BSs in the specific area is handled by small BSs of that area. In assumed simulation scenarios, the number of allocated macro BSs is fixed and different for each demography class (Table IV). To ensure full signal coverage and minimal capacities in an area with a specific demography class, the number of fixed macro BSs is selected for analyses. The number of estimated macro BSs for specific demographic classes on an area of one square kilometer is selected considering real-world practical macro BSs installation limitations.

TABLE IV. NUMBER OF ALLOCATED BSs PER DEMOGRAPHY AREA

Demography class	Number of allocated macro BS per km ²	Minimal number of allocated small BS per km ²	Maximal number of allocated small BS per km ²
Indoor hotspot	8	1176	11801
Dense urban	4	180	1820
Urban	2	14	155
Rural	1	1	10

Simulation analyses are performed using the Matlab R2018a simulation tool. In total, 10 simulation runs per scenario and 30 simulation runs for each demography area have been performed, what results with the total number of 120 simulations for all demography areas used in the analyses. Simulation time was measured in the order of microseconds, what ensures fast obtaining of simulation results. Although the Tx power adjustment of macro BSs can increase the EE RANs [18], the last simplification used in the analysis is related to neglecting the Tx power adjustment of macro BSs. In the next section, we discuss the results obtained by calculating the data EE KPI metric for the presented simulation scenarios in the area with a specific demography class.

V. RESULTS

In Table IV, for each area with a specific demography class, the number of allocated macro and small BSs is presented. According to Table IV, the number of allocated macro and small BSs is adjusted according to traffic DV requirements. The number of allocated macro BS(s) is fixed and differs for each demography area, where lower values of installed macro BSs are in the areas with lower user density and vice versa (Table IV). Similarly, the minimal and maximal number of small BSs is allocated with respect to the DV requirements, where areas with lower user density have a lower number of allocated small BSs and vice versa (Table IV). Consequently, data traffic requirements for demography classes with a lower number of active users can be satisfied through the allocation of a lower number of small BSs, and vice versa.

For each simulation scenario and each observed demography class (indoor hotspot, urban, suburban, and rural), Figs. 2 present results of the data EE metric expressed in Mbit/J. As shown in Figs. 2, calculated data EE metric decreases as the number of active users decreases, and vice versa. These results are characteristic for each simulated area of every demography class. When the active number of users decreases, Figs. 2 indicate that Scenario 1 and 2 have a monotonic decrease of data EE metric, while Scenario 3 exhibits a linear decrease of data EE metric. Hence, results show that Scenario 3 offer to TOs worst small BSs deployment strategy from the perspective of data EE, since these scenarios have been characterized with the lowest average data EE in comparison with the average data EE of Scenario 1 and 2. Lowest average data EE of Scenario 3 is a consequence of small BSs deployment and operations strategies, which are not performed following changes in the

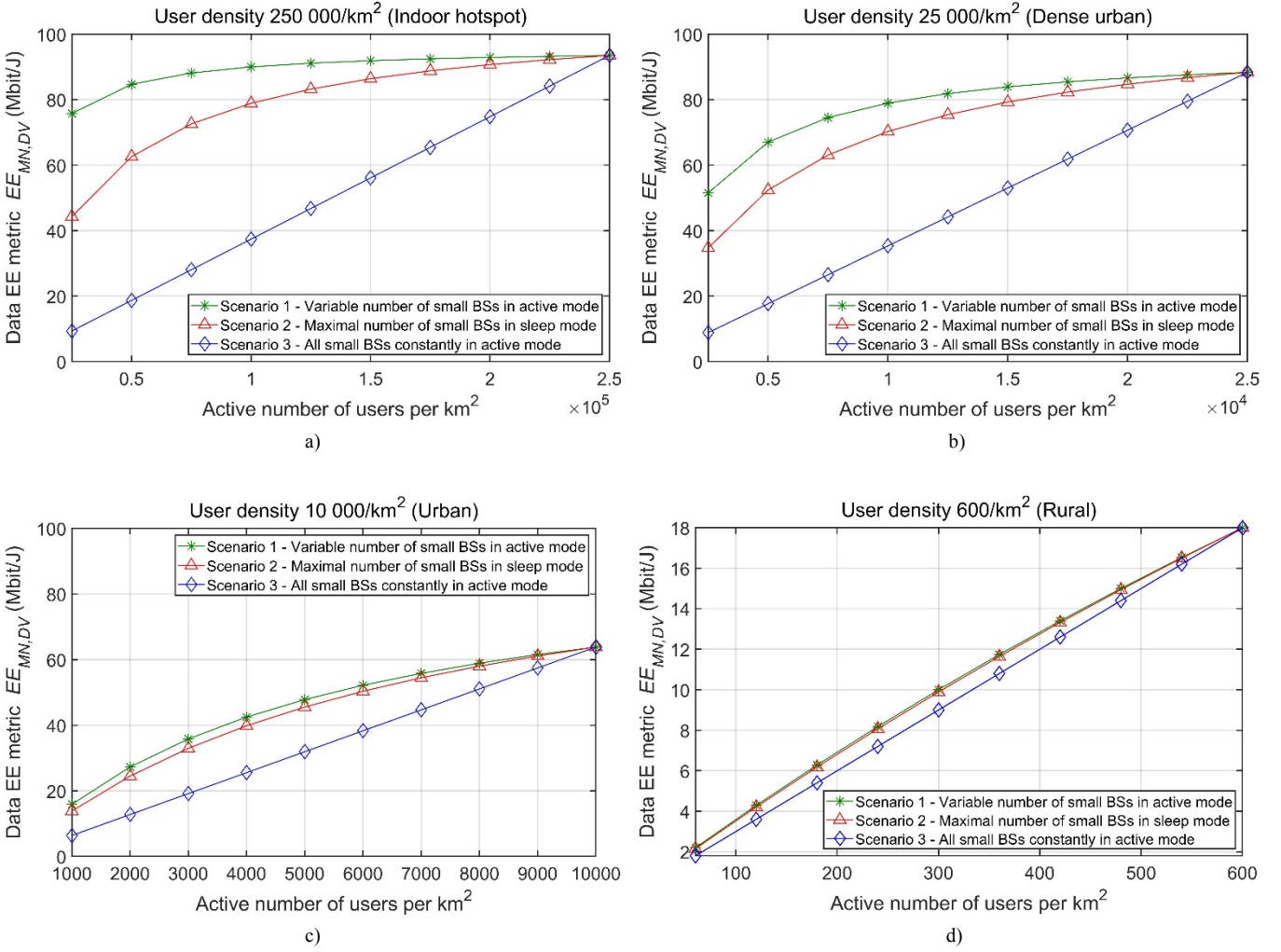


Fig. 2. Data EE metrics (Mbit/J) for users density per 1 km^2 in the: a) indoor hotspot scenario; b) dense urban scenario; c) urban scenario; d) rural scenario.

number of users and corresponding DVs of specific demography area. Hence, Scenario 3 is the least favorable approach in terms of *deployment and operation strategy* of small BSs. In terms of data EE, for all demography areas, the best 5G small BSs *deployment strategy* is Scenario 1 (Figures 2). This is a consequence of the gradual installation of new small BSs according to the increase in traffic demands at specific locations of some demography area. Furthermore, Scenario 2 represents the best *operation strategy* for small BSs, where the maximal number of small BSs are in sleep mode at any moment, and small BSs are deactivated and activated depending on the decrease or increase of data traffic demand, respectively.

According to Figs. 2, rural demography class having the lowest user densities has the lowest absolute values of data EE KPI metrics. This is because TOs need to deploy a lower number of small BSs to accommodate the requirements of a small number of users in rural demography class. This results in the domination of macro BSs power consumption over the power consumption of micro BSs, which leads to the least energy-efficient data transfer per Joule of consumed energy.

Furthermore, Figs. 2 show for all demography classes, that increase in user densities results in a converge of data EE metric towards the maximal value of the EE metric. This is the result of the inability of different deployment and operation scenarios to give any benefit in terms of EE improvement,

since all network resources must be activated to satisfy maximal demand for data traffic transmission. The fact that an increase of data EE metric is followed with an increase of user densities in any demography class, is a consequence of the need for installation of a larger number of small BSs in areas having a higher number of users. Since small BSs have lower power consumption than macro BSs and higher spectral efficiencies (Table I), the higher number of installed small BSs positively impacts on data EE metrics. This is why areas with higher user densities have better data EE metrics in terms of absolute values (for indoor hotspot up to 92 Mbit/J (Fig. 2a) and for rural demography area up to 18 Mbit/J (Fig. 2d)).

Also, Figs. 2. indicate that distinction among the curves presenting data EE metric of various simulation scenarios increases for demography classes having higher user densities and vice versa (higher distinction for indoor hotspot (Fig. 2a) compared with rural demography area (Fig. 2d)). This is due to the necessity of installing a higher number of small BSs which must accommodate increased traffic demand, which further contributes to larger differences among data EE curves of simulation scenarios performed for the same demography class. Accordingly, the demography class with the highest difference among data EE metric curves for different scenarios is the indoor hotspot (Fig. 2a). This implies that small BSs allocation approach directly impacts on data EE metrics, which will have lower differences among various

scenarios in those demography areas having lower user density (lower number of small BSs), and vice versa (Figs. 2).

A. Discussion

To achieve higher EE, a TOs *deployment strategy* of the 5G RAN has to take into consideration future traffic capacity demands and based on these demands perform continuous installation of the new 5G small BSs. Also, to achieve better EE, TOs *operation strategies* for the 5G mobile networks must include dynamic activation and deactivation of the small BSs depending on the data traffic variations for any demography class. The least desirable 5G RAN *operation and management strategy* in terms of data EE is a legacy approach, where the maximal number of BSs (macro and small) are constantly active and allocated in maximal numbers needed for satisfying future area data traffic demands (Scenario 3). This approach should be replaced with one or a combination of the more energy-efficient approaches (Scenario 1 and 2) discussed in this paper.

The analysis in this work has been performed for the 5G HetNet architecture designed to satisfy data traffic demands prescribed by ETSI standards for specific demography class. Hence, real-world implementations of 5G HetNets might vary in terms of the number of active users, and accordingly in the allocated number of BSs (micro and small). Therefore, it can be expected that real-world implementations of 5G HetNets might have different values of the data EE metrics, than those presented in Figures 2. Nevertheless, data EE analysis and values obtained and presented in this paper can be used as a point of reference for future study of this topic. Also, the trends of curves presented in Figs. 2 will not deviate to a greater extent for any 5G HetNet architecture and can be used as a reference, which points to how trends of data EE metrics will be changed for different users densities in areas having different demography classes.

VI. CONCLUSION

The 5G mobile networks must accommodate challenging demands related to ensuring high data rates, low delays and high reliability to the continuously increasing number of mobile users. Ensuring these demands greatly affects network energy consumption and consequently the EE of the radio part of the mobile access network. Therefore, the analysis presented in this paper takes into account the impact of different user densities in various demography classes (indoor hotspot, dense urban, urban and rural) on the data EE metric of 5G mobile network. Changes in data EE metric has been analyzed for three different simulation scenarios and for four demography classes, which differ in user densities per square kilometer. Obtained simulation results show that different user densities for any demography class have a significant impact on the data EE metric of 5G RAN. With an increase in user density and corresponding data traffic volumes for any demography class, the data EE metric increases, and vice versa. Hence, obtained results show that an increase in user density has a positive impact on data EE metrics, in any of the demography classes. Furthermore, this paper analyses the most energy-efficient 5G HetNet small BS deployment and operation strategy. Obtained results show that the most efficient deployment and operation strategies are based on the continuous installation of new small BSs and dynamic activation of installed BSs according to user density variations. Presented results can help TOs in performing more

energy-efficient deployment and operation strategies of 5G network implementations for different user densities allocated in a specific demography area. Our future research activities will take into account the impact of user density on other standardised RAN EE metrics.

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