Modeling and Analysis of Data and Coverage Energy-efficiency for Different Demographic Areas in 5G Networks

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***Abstract*—It is expected that fifth-generation (5G) mobile networks will need to accommodate vast data traffic volumes. The practical implementation of 5G networks is further challenged by the presence of versatile demographic areas differing in user density and expected transmission rates. Accommodating the increased traffic demands in such versatile demographic areas mandates the installation of different in size, number and capacity 5G base stations (BSs), which will have an impact on the energy consumption of the 5G network. In this paper, for the square kilometer area of the radio part of the 5G network, standardized network energy-efficiency (EE) metrics are presented. The EE analysis of the 5G network was performed for four different demographic areas (indoor hotspot, dense urban, urban and rural) and two standardized data (bit/J) and coverage (m^2/J) EE metrics. To determine how the different 5G BSs deployment strategies affect the network's EE, five different 5G BSs installation and operation strategies have been analyzed for each demographic area. Interpolation functions expressing the impact of the data volume (DV) on the data and coverage EE metrics have been developed for each demographic area and network installation and operation scenario. The obtained results show that the DVs of the different demographic areas significantly impact the standardized EE metrics.**

Index Terms— **5G, base station (BS), cellular, demography, density, energy-efficient, green, key performance indicators (KPI), metric, mobile, network, traffic, users.**

I. Introduction

As wireless mobile communication technology advances, energy efficiency (EE) is becoming one of the key concerns. Each new generation of mobile network is more energy demanding. This is a consequence of the new requirements related to an increase in the number of users and traffic data volume (DV) [1], [2]. Due to the continuous increase in the number of users and mobile services, the global mobile data traffic increases and estimations predict its global growth by 31% annually between 2019 and 2025. Furthermore, by the end of 2019, the total global mobile data traffic reached around 33 EB per month and it is expected to reach 164 EB per month in 2025. Fourth generation (4G) long term evolution (LTE) technology will remain the dominant mobile access technology during that period. By the end of 2025, it is predicted that 5G will account for about 45% of the total mobile data [3]. This is a consequence of the global trends according to which the world is going towards ubiquitous networking where not only are humans communicating with each other but also devices that are becoming smarter in terms of the possibility to communicate with each other without human interaction. Since "*everything to everything*" communication is expected, there is a high demand for network capacity, throughput and coverage followed by the necessity of ensuring network reliability and availability.

Fifth-generation (5G) mobile networks are designed to satisfy such demands through the practical implementation of three key features: enhanced mobile broadband (eMBB) dedicated to ensuring high capacity and throughput demands, massive machine-type communications (mMTC) dedicated to connecting a massive number of devices that require a machine to machine (M2M) communication and ultra-reliable and low latency communications (URLLC) which should satisfy the high requirement for low latency critical and real-time communications [4]. To achieve this, 5G is deployed as a heterogeneous network (HetNet) comprised of outdoor macrocells for wide signal coverage and small cells (microcells, picocells, femtocells) for satisfying the throughput demands of a smaller geographical area, which can be both indoors or outdoors.

Since the frequency bands used by the previous generations of cellular networks are getting congested, thus lacking the possibility of using wide channel bands, 5G standardization has envisioned the possibility of communicating in millimeter wave (mmW) frequency bands [5]. The advantage of mmW frequencies is the possibility of offering higher throughputs to the users through the exploitation of wider channel bands. On the other hand, the disadvantage of mmW communications is reflected in the short coverage range due to high propagation, penetration and rain attenuation losses. The consequence of this predetermines the 5G network architecture as a heterogeneous architecture composed of a smaller number of macro BSs and a larger number of small BSs, that are needed to compensate for a short coverage range in locations with a high traffic demand (hot-spots) [6]. However, the amount of installed 5G BSs will depend on the user density and its demand for traffic capacity. This impacts the overall number of installed macro and

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especially small BSs.

Hence, the differences among the demographic areas in terms of user density and the corresponding traffic volumes will require different 5G network configurations in terms of the number and capacity of BSs. This will further result in different influences on the 5G network EE. With an increase in the needed number of macro-cell and small-cell BSs, the power requirements of 5G networks increase significantly. This is the reason why an approach based solely on maximizing network coverage, capacity and user throughput at the expense of energy consumption (EC) presents not only an economic but also an environmental issue. Consequently, EE has emerged as one of the Key Performance Indicators (KPIs) for 5G networks which must be taken into account during network planning, deployment and usage phase.

In order to express EE as a KPI, the same set of EE metrics have been recently defined in terms of the standards and recommendations issued by the relevant standardization organizations such as the 3rd Generation Partnership Project (3GPP) [7], the European Telecommunications Standards Institute (ETSI) [8] and the International Telecommunication Union – Telecommunications Standardization Sector (ITU-T) [9]. The EE KPIs defined in these standards will help the mobile network operators (MNOs) to compare various types of network elements, design options and the EE of the live network during the network life cycle [7]. The standards use three fundamental parameters including EC, data volume and coverage area in order to define the two standardized KPIs which are data (bit/J) and coverage (m^2/J) EE metrics.

Considering the challenges related to the MNOs implementation of 5G networks in different demographic areas, in this paper the impact of different demographic areas (indoor hotspot, dense urban, urban and rural) on the EE metrics for 5G HetNets has been analyzed. Additionally, to understand how the different 5G BSs deployment strategies impact the EE of 5G networks for each of the demographic area, five different 5G BSs installation and operation approaches have been considered. The data and coverage-based EE metrics have been calculated and compared, indicating a significant impact on the network EE concerning user density and 5G network deployment and operational strategies in a specific demographic area. The new contributions of this work can be summarized as follows:

1) The presentation of data and coverage EE metrics as KPIs standardized by the relevant standardization bodies for expressing the data and coverage EE of 5G HetNets.
2) The conducting of analysis into the trends in the changes in the data and coverage EE metrics impacted by variations of the data volumes (DVs) in four demographic areas for five different 5G HetNet installation and operation scenarios.
3) Proposal of interpolation functions that express the relationship between the data or coverage EE metrics and DVs for five 5G HetNet installations and operation scenarios in different demographic areas.

The rest of the article is organized as follows. In Section II, a brief literature overview of the previous research activities related to the analysis of the data and coverage EE metrics in cellular networks is presented. Section III explains the standardized data and coverage-based EE metrics. The simulation scenario of the 5G network used for the analysis of the network's EE is presented in Section IV. In Section V, the obtained results related to the user number in specific demographic areas and the BSs deployment and operation strategy impact on the EE metrics of 5G networks have been compared and discussed. Finally, some concluding remarks are given in Section VI.

II. Related work

In the last decade, the research area dedicated to improving the EE metrics of the radio part of the cellular access networks have gained significant attention from the academic and industry community. In our initial work [10], the EE metrics of the 2^{nd} generation (2G), 3^{rd} generation (3G) and 4G macro BS sites in urban regions have been analyzed. It is shown that the macro BSs inter-site distance and transmit (Tx) power levels have a significant impact on the network EE metrics such as area bit-per-Joule and the area power consumption metric. The authors in [11] proposed a green communication model for 5G networks according to which the increased power consumption of networks using dense small cell deployments can be alleviated using BS sleep mode strategies. The solutions for increasing the EE of mobile cellular networks are summarised in survey work [12] under four categories: resource allocation related to maximizing the amount of information that can be reliably transmitted per Joule of energy, network planning and deployment-related to increasing the coverage area per consumed energy, energy harvesting from clean and renewable energy sources and green hardware design dedicated to improving energy efficiency.

In [13], it is shown that it is possible to reduce the overall network EC by up to 70% by transforming the network from legacy LTE deployments to 5G new radio networks. The results presented in [14] further confirm that heterogeneous cellular networks can increase the area and bit-per-Joule EE by adding small BSs in combination with the reduced transmission power of the macro BS. Furthermore, in [15], we have analyzed the impact of different 4G BS deployment strategies in HetNets on EE metrics. The obtained results show how the deployment of cellular HetNets in terms of BSs inter-site distances and transmit (Tx) power scaling affects the power-per-unit area and energy-per-bit and unit area metrics. The authors in [16] have developed an analytical framework in which the key to achieving high EE in 5G networks is based on network densification by adding many small BSs in addition to the implementation of massive multiple-input multiple-output (MIMO) technology.

Although presented related work analyses EE of cellular networks by means of different EE metrics, the analysis giving insights on how different user densities influence on standardized EE metrics of 5G networks has not yet been performed. According to our knowledge, for the first time, a model based on interpolation functions expressing the impact of different data volumes in versatile demographic areas with distinct user densities based on the standardized data and coverage EE metrics of 5G networks have been presented and analyzed. The results of this analysis can be of particular interest to the MNOs since the obtained results offer general insights into the EE-user density trade-off and eventually they can help the MNOs pursue energy-efficient 5G network implementation strategies for specific demographic areas.

Hence, the contributions of this article are of special interest concerning the two main phenomena that will impact on the installation and management of 5G HetNets in the upcoming decades. The first is related to the intensity of the DVs that will continually increase due to the growth in the users' requirements for new and generally more throughput-demanding services. This will particularly contribute to the massive implementation of Internet of Everything (IoE) applications which will be used in medical, agriculture, industrial, transport, automotive, augmented/virtual reality, smart house and smart city environments. This is where 5G HetNets are seen of as the main enablers of these applications in practical implementations. The second phenomenon is related to the continuous increase in the world population at the global level to which every new generation of the mobile network has been offered faster than the previous one. Although the deployment of 5G HetNets in developed countries is expected to be faster than in developing countries, these countries will also experience the benefits of 5G HetNets sooner than they experience the benefits of any of the previous mobile network generations. This is due to the technological advancements made in the mass production of 5G network equipment, the users' demands and the expectations of the possibility of using the latest mobile network services in addition to the commercial interest of telecom providers in new and increased revenues.

Therefore the contributions of this article take into account these challenges through the presentation of cognitions related to how the different DVs in versatile demographic areas impact the EE metrics of 5G HetNets. This impact is precisely formulated for different 5G HetNet installations and management scenarios. The formulation is based on the development of interpolation functions which can be used for the estimation of the data and coverage EE metrics in different demographic areas impacted by the future increase in user density and corresponding DVs.

III. STANDARDIZED ENERGY-EFFICIENCY METRICS

The definition of the methods and metrics that can be used to measure the EE performance of mobile radio access networks has been standardized by the ETSI standard (ES) 203228 [8]. According to this standard, the equipment that can be used in the process of mobile network (MN) EE estimations can contain elements such as BSs, BS site equipment, backhaul equipment and radio controllers. Since the analysis of the EE measurements and the complete MN are not viable, the ETSI standard allows the overall MN to be split into smaller sub-networks for analyses. For simplicity and feasibility, the analysis of the EE of 5G HetNets in this work was performed for the radio part of the network containing only radio BSs and for an area of one square kilometer (Fig. 1).

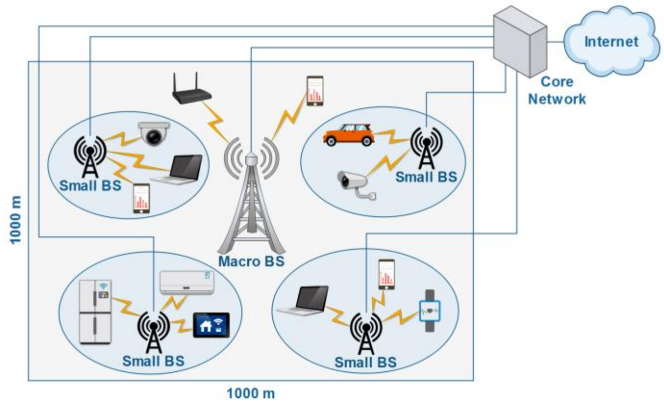

Fig. 1. Simulation model of a 5G HetNet.

Also, the ETSI standard in [8] provides a method of categorization of the test parameters that can be considered for the EE measurements in operational networks. EC, data volume (DV) and coverage area (CoA) are the test parameters defined by the ETSI standard used in the further analysis. For the evaluation of EE trends, the ETSI standard in [8] defines the different sub-network demographic areas (classes) based on the different population densities. The common demographic areas (urban, suburban and rural) defined by the ETSI standard [8] have been extended in the analysis presented in this paper with one additional demographic area (class) known as an indoor hotspot introduced in the latest standard ETSI TS 122 261 [17].

The ETSI ES 203 228 [8], 3GPP [7] and ITU-T [9] standards define the two high-level EE KPI metrics. The first EE KPI metric is based on data capacity and expresses network data energy efficiency ($EE_{MN,DV}$) as the ratio between the MN data volume (DV_{MN}) and the MN EC (EC_{MN}) [8]:

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

DV_{MN} in relation to (1) is defined as the total data volume delivered by all equipment (BSs) over the measurement period of time T. The total data volume DV_{MN} takes into account the downlink (DL) and uplink (UL) communications and is assumed to be composed of packet and circuit-switched data volumes. The EC_{MN} is defined as the sum of the EC of the equipment included in the MN under investigation during the same time period T. Hence, this EE KPI metric represents the amount of data that can be reliably transmitted per Joule of energy consumed by the network.

The second EE KPI metric is based on coverage area. This EE KPI expresses the MN data energy efficiency ($EE_{MN,CoA}$) as the ratio between the MN coverage area (CoA_des_{MN}) and the MN EC (EC_{MN}) [8]:

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 full active/Tx power scaling mode (W)
5G macro	10	100	3	3	/	2000/1600
5G small	6	800	1	4.8	5	50/40

TABLE II
REFERENCE PARAMETERS FOR THE VARIOUS DEMOGRAPHIC AREAS

Demography area (class)	Downlink experienced data rate (Mbit/s)	Uplink experienced data rate (Mbit/s)	Maximal user density (/km^2)	Users activity factor (%)	Area traffic demand (DV) for 10% user activity (Tbit/s/km^2)	Area traffic demand for 50% user activity (Tbit/s/km^2)	Area traffic demand for 100% user activity (Tbit/s/km^2)
Indoor hotspot	1,000	500	250,000	10 - 100	5.67	28.33	56.67
Dense urban	300	50	25,000	10 - 100	0.87	4.37	8.75
Urban	50	25	10,000	10 - 100	0.075	0.37	0.75
Rural	50	25	600	10 - 100	0.0045	0.022	0.045

$$EE_{MN,CoA} = \frac{CoA\_des_{MN}}{EC_{MN}} \ [\text{m}^2/\text{J}] \quad (2)$$

where CoA_des_{MN} is defined as the designated coverage area of the selected sub-network and EC_{MN} is the yearly EC. This EE KPI metric expressed in square meter per Joule (m^2/J) in relation (2) represents the size of the MN area that can be covered per Joule of consumed energy. Therefore these two standardized EE KPI metrics have been used for the EE analyses of 5G networks based on the simulation scenario presented in the next section.

IV. SIMULATION MODEL

The network model used for the simulation analysis of the 5G HetNet EE has been illustrated in Fig. 1. To calculate the EE KPI metrics, a reference area of one square kilometer (1 km^2) was used for the simulation of the analyzed sub-networks based on the heterogeneous (HetNet) architecture containing both macro and small BSs (Fig. 1). Macro BS(s) are used for ensuring wide area signal coverage and partially for satisfying traffic demands while small BSs are used for covering small hot-spot areas with large traffic demands. Although the real implementation of 5G networks will be composed of different types of small BSs (micro, pico or femto BSs), for simplicity and without a loss of generality, only one general type of small BSs is used in the analysis of this study. The reference parameters regarding spectral efficiency, channel bandwidth, the number of sectors, data capacity and the power consumption of the small and macro 5G BSs used in the analysis have been presented in Table I [18]. According to [18], the configuration and power consumption parameters of macro and small 5G BSs used in the analysis (Table I) are characteristic of the initial market models of 5G macro and micro BSs. To further simplify the analysis, wireless local area network (WLAN) offloading in 5G networks has been neglected and device to device communication with data relaying is assumed to be performed over the existing BSs in the analyzed 5G network.

Furthermore, simulations have been performed for four different demographic areas, the details of which are presented in Table II. According to Table II, the demographic areas differ in terms of the maximal user density per square kilometer and the experienced DL/UL data rates. The values of the parameters presented in Table II are selected from the standard ETSI TS 122 261 [17]. Based on these values, a total area traffic DV which takes into account the UL and DL transmission for a specific demographic class has been calculated and presented in Table II. To model the impact of the various demographic area's traffic demands on the network EE KPI metrics, the total number of active users and corresponding DVs have been scaled by the user's activity factor ranging between 10% and 100% of the maximal user density for a specific demographic class (Table II).

A. Simulation scenarios

Five different small and macro 5G BSs deployment and scheduling scenarios for each EE KPI metric and demographic area have been simulated in the analysis. Small and macro BSs deployment and operation scenarios are related to the concept of installing BSs and scheduling the BS activity with the goal of improving the network EE of the analyzed 5G HetNets. Each simulated small and macro BSs deployment and management scenario has been presented in Table III. The analyzed simulation scenarios are based on accommodating a rapid increase in data users and corresponding DVs in the upcoming period of 5 - 10 years which the 5G HetNets are planning for in terms of the number of allocated BSs and resource capacities.

For each demographic area of a square kilometer, a different number of fixed macro BSs is assumed to be allocated (Table IV). The number of allocated macro BSs for each of the analyzed demographic areas is selected based on the criteria according to which the capacity of all installed macro BSs must accommodate the minimal DV of the specific area and ensure full signal coverage at any moment. The percentages of the transferred maximal and minimal DVs related to the macro BS(s) for the minimal (10%) and maximal (100%) DVs of the

TABLE III
CHARACTERISTICS OF SIMULATION SCENARIOS

Simulation scenarios	Small BSs installation approach	Macro BSs number	Small BSs sleep mode activity	Tx power scaling of macro BS(s)	Tx power scaling of active small BSs
Scenario 1 -Variable number of small BSs in active mode	Continuous according to an increase of DV	Fixed-10 year predictions	No	No	No
Scenario 2- Maximum number of small BSs in sleep mode	Max. number based on 10-year predictions	Fixed-10 year predictions	Yes, according to variations of DV	No	No
Scenario 3 -All small and macro BSs constantly in active mode	Max. number based on 10-year predictions	Fixed-10 year predictions	No	No	No
Scenario 4 - Variable number of small BSs in Tx power scaling mode	Continuous based on increase of DV	Fixed-10 year predictions	Yes, according to variations of DV	No	Yes, according to variations of the DV
Scenario 5 - Variable number of small and macro BSs in Tx power scaling mode	Continuous based on an increase of DV	Fixed-10 year predictions	Yes, according to variations of DV	Yes, according to variations of DV	Yes, according to variations of the DV

TABLE IV
NUMBER OF ALLOCATED BSS PER DEMOGRAPHIC AREA

Demog. 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	Percentage (%) of transferred DV by macro BSs in overall area DV for DV range 10 % - 100%
Indoor hotspot	8	1176	11801	0.420 – 0.042
Dense urban	4	180	1820	1.370 – 0.137
Urban	2	14	155	8.00 – 0.80
Rural	1	1	10	6.67 – 66.70

specific demographic areas are presented in Table IV.

Considering the space limitation challenges that arise with the practical deployment of a large number of macro BSs per 1 km^2, it is reasonable to believe that the number of allocated macro BSs for a specific demography area used in this analysis is realistic (Table IV) and in line with the practical implementation. Also, all simulation scenarios used in the analysis assume the allocation of a fixed number of macro BSs per analyzed demographic area of one square kilometer (Table III). Such an assumption regarding the macro BS allocation policy is in line with the common telecom operator approach related to the deployment of the maximal number of needed macro BSs in the future period of 10 years. The number of macro BSs must satisfy the capacity and coverage needs for the upcoming period of 10 years, which is estimated to be the lifetime of the macro BSs. Further, the clarification of the proposed simulation scenarios used for the analysis of the standardized EE metrics in 5G HetNets has been presented.

B. *Simulation Scenario 1*

In the first simulation scenario (Scenario 1 in Table III), the installed number of small BSs is gradually increased according to the increase in demand to accommodate the ascending DV capacities in the analyzed HetNet. Scenario 1 assumes a *variable number of small BSs working constantly in active mode* (Table III). An increase in the number of installed BSs will depend on the trends in the increase of DVs during the network operation period. This scenario corresponds to the MNO approach based on the continuous installation of new small BSs during the 5 - 10 year period. Installation is performed according to an increase in the number of users and corresponding DVs at the locations of the hotspots. The installed macro and small BSs work constantly in active mode without any power efficiency scheme implemented in terms of decreasing the transmitted (Tx) power adaptation for the purpose of reducing the EC in low traffic activity periods.

C. *Simulation Scenario 2*

The second scenario (Scenario 2 in Table III) assumes that the maximal number of installed small BSs will satisfy the expected future needs of the DV capacity for the MNO. In simulation Scenario 2, only the small BSs in the areas with an excessive capacity demand beyond those which can be accommodated by the macro BSs are active. Other small BSs are allocated and these BSs are in sleep mode. The activation of these BSs is scheduled according to the increase in the traffic DV in a specific location. Hence, in Scenario 2, *the maximal number of small BSs is in sleep mode* at any moment (Table III). This scenario simulates the MNO approach based on the continuous adaptation of small BSs activity according to the traffic DV variations.

For small BSs in sleep mode, the instantaneous power consumption is modeled on 10% of the total maximal small BSs power consumption (Table I). As in Scenario 1, the installed macro BS(s) work constantly in active mode without any power efficiency scheme implemented in terms of the Tx power adaptation for the purpose of decreasing the EC in low traffic periods with low activity (Table III).

D. *Simulation Scenario 3*

In the third simulation scenario (Scenario 3 in Table III), similar to Scenario 2, the maximal number of small BSs for the expected future capacity needs is assumed to be installed by MNO. As in Scenarios 1 and 2, the installed macro BS(s) work constantly in active mode while also lacking the implementation of any power efficiency scheme. However, in Scenario 3, *all small and macro BSs are constantly active* (Table III) and transmitting at maximum Tx power which results in maximal power consumption. Scenario 3 represents the traditional MNO small and macro BSs allocation approach, lacking any activity or Tx power scheduling of the small and macro BSs according to the variations in traffic DVs. Although less favorable from the perspective of network EE, Scenario 3 is included in the analysis to compare how the legacy approach based on the constant activity of all allocated small and macro BSs affects the EE of the HetNet.

TABLE V
AVERAGE DATA AND COVERAGE EE FOR THE ANALYZED SCENARIOS

Small BS scheduling scenario	Description of the scenario	Average data EE for 1 km^2				Average coverage EE for 1 km^2			
		Indoor hot spot area (Mbit/s/J)	Dense urban area (Mbit/s/J)	Urban area (Mbit/s/J)	Rural area (Mbit/s/J)	Indoor hot spot area (m2/MJ)	Dense urban area (m2/MJ)	Urban area (m2/MJ)	Rural area (m2/MJ)
Scenario 1	Variable number of small BSs in active mode	89.38	78.58	46.15	10.56	0.14	0.73	4.18	13.99
Scenario 2	Maximal number of small BSs in sleep mode	79.33	71.74	44.44	10.49	0.11	0.61	3.92	13.85
Scenario 3	All small and macro BSs constantly in active mode	51.43	48.60	35.11	9.90	0.05	0.32	2.70	12.68
Scenario 4	Variable number of small BSs in Tx power scaling mode	109.91	94.33	51.60	10.88	0.17	0.86	4.58	14.32
Scenario 5	Variable number of small and macro BSs in Tx power scaling mode	111.73	98.23	57.69	13.20	0.17	0.91	5.23	17.49

E. Simulations Scenarios 4 and 5

The fourth simulation scenario (Scenario 4 in Table III) has the same macro and small BSs deployment policy as presented in Scenario 2. This means that the installed number of small BSs is gradually increased according to the trend of accommodating the increasing need for DV capacities in the analyzed demography area. In addition to this deployment approach, small BSs Tx power scaling according to daily traffic variations have been incorporated in Scenario 4. Hence, scenario 4 assumes the installation of a *variable number of small BSs operating in Tx power scaling mode* (Table III). It is shown in [15] that the Tx power scaling of small BSs can further contribute to the improvement of the cellular network's EE. A conservative assumption related to the effects of Tx power scaling on the improvement of small BSs energy efficiency is used in this analysis. It is assumed that Tx power scaling can further contribute to the reduction of the average power consumption of small BSs on a daily basis by 20% (Table I) in comparison with approaches having constantly active small BSs transmitting at maximal Tx power.

Additionally, the fifth simulation scenario (Scenario 5 in Table III) is essentially the same as Scenario 4 in terms of the deployment strategy of the small and macro BSs. However, besides the Tx power scaling of the small BSs, this scenario assumes that macro BSs also scale the Tx power according to the space and time variations of the data traffic. It is proven in [19] that such an approach can contribute to the improvement of the network's EE. Hence, scenario 5 assumes the installation of a *variable number of small and macro BSs operating in Tx power scaling mode* (Table III). In the case of all scenarios, the selection of the number, capacity and Tx powers of the macro BSs allocated in the analyzed demographic areas is performed in such a way that the area's full coverage with the 5G signal must be ensured and that the minimal data capacity for the 5G HetNet in the analyzed demographic area must be guaranteed.

V. RESULTS

The results obtained for the simulation scenarios introduced in the previous section have been further analyzed and discussed. According to Table IV, the allocation of a minimal and maximal number of small BSs in the analyzed area of one square kilometer will be different for the different demographic areas. The allocation of a specific number of macro and small BSs has been performed with respect of the necessity of satisfying the transfer of the overall traffic DV for any user density in each of the analyzed demographic areas. As expected, higher values for the minimal and a maximal number of allocated small BSs (Table IV) will be in the demographic areas with higher user densities per km^2 (Table II), and vice versa. This is because higher user densities impose higher overall area traffic volumes where the transmission requires a higher network capacity that will be obtained through the installation of a higher number of small and macro BSs.

A. Data energy-efficiency metric

The higher values of the minimal and maximal number of allocated small BSs in the demographic areas with higher user densities are reflected in the results presented in Fig 2 showing the results for the data EE metric in Mbit/J for the different demographic areas. According to the results presented in Fig 2, for each of the analyzed demographic areas (indoor hot spot, urban, suburban and rural), the data EE metric (Mbit/J) increases when there is an increase in the number of active users (subscribers) in the network, and vice versa. This increase is monotonic for Scenarios 1, 2, 4 and 5 while Scenario 3 has a linear increase of the data EE metric (Figs 2). According to what is presented in Figs.2 and 4a, these scenarios are characterized by a higher average data EE metric in comparison with the average data EE efficiency of Scenario 3.

The obtained results indicate that in comparison with the traditional installation and management approach simulated in Scenario 3, Scenarios 1, 2 and especially 4 and 5 offer MNOs a better small BSs deployment strategy from the perspective of the data EE metric. The higher average data EE of Scenarios 1 and 2 in comparison with Scenario 3 is a consequence of the small BSs deployment strategies performed in a continuous correlation with the increase in the number of users and corresponding DVs of a specific demographic area. The higher average data EE of Scenarios 4 and 5 in comparison with Scenarios 1 and 2 is due to the additional implementation of the Tx power scaling of micro BSs in Scenario 4 and macro and micro BSs in Scenario 5 which further contributes to the

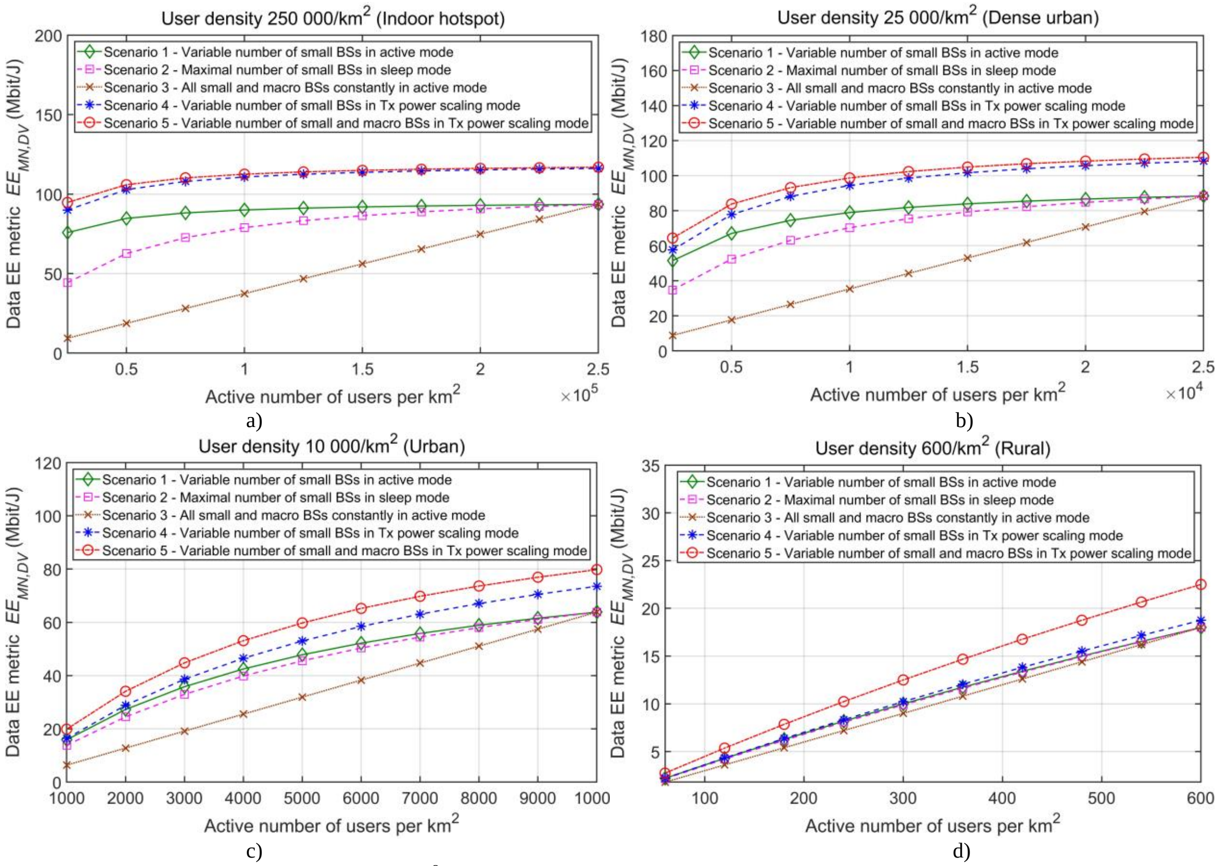

Fig. 2. Data EE metrics (Mbit/J) for users density per 1 km^2 in the: a) indoor hotspot scenario; b) dense urban scenario; c) urban scenario; d) rural scenario.

improvement of the data EE metric.

In terms of the data EE metric, the best *allocations of the new small 5G BSs* strategy for all demographic areas are those simulated in Scenarios 1, 4 and 5 (Fig.2). The best small BSs operation strategy for MNOs is based on Scenario 4, the *maximal possible number of installed small BSs will be in sleep mode at any moment* and small BSs activation and deactivation will be performed according to the variations in traffic DVs. The best overall BSs installation and operation strategy for MNOs is based on Scenario 5, where the *maximal possible number of installed small and macro BSs will be in sleep* mode at any moment and the BSs Tx power scaling will be performed according to variations in traffic DVs.

Regarding the absolute values of the data EE metrics presented in Fig. 4a, it can be observed that the highest data EE has the demographic area with the highest user density (indoor hotspot), and vice versa. This is the consequence of the fact that demographic areas with a higher user density require a higher number of small BSs (Table IV) which results in a higher spectral efficiency and lower maximal instantaneous power consumption. This significantly contributes to the increase in the amount of data that can be transmitted per Joule of energy (data EE metric).

In the case of the highest user densities, according to Fig.2, each graph for every test scenario eventually converges on the maximal data EE metric of a specific demographic area (Scenarios 1 - 3 and Scenarios 4 - 5). This is a consequence of the fact that in the case of the highest user densities, the data EE metric cannot benefit from either of the analyzed deployment and operation scenarios. This is due to the fact that all available HetNet resources (maximal number of small and macro BSs) must be activated to exploit the full BSs Tx power and capacity in order to satisfy the maximal traffic DVs. Furthermore, in Fig.2, it can be observed that the differences in the data EE metrics will be lower for demographic areas with lower user densities. The reason for this can be found in the lower overall number of active users and the corresponding DVs which implies the use of a lower number of small BSs in a specific demographic area. The most notable example of small differences between the data EE metrics is presented in Fig. 2d for the rural demographic area. Therefore a lower number of small BSs in demographic areas with a lower user density leads to a smaller difference in the overall HetNet EC among the different demographic areas and corresponding scenarios. This further results in the reduction of differences among the data EE metrics of the different scenarios.

B. Coverage energy-efficiency metric

The simulation results indicating the impact of the user density in the different demographic areas on the coverage EE metric (m^2/MJ) are presented in Fig.3. Unlike the data EE metric, the coverage EE metric decreases when the number of active users increases in every demographic area and vice versa. This is a consequence of the fact that less populated areas are characterized by the demand for the transfer of lower traffic DVs which further imposes a lower number of active BSs. Due to the lesser number of BSs in the areas with lower user

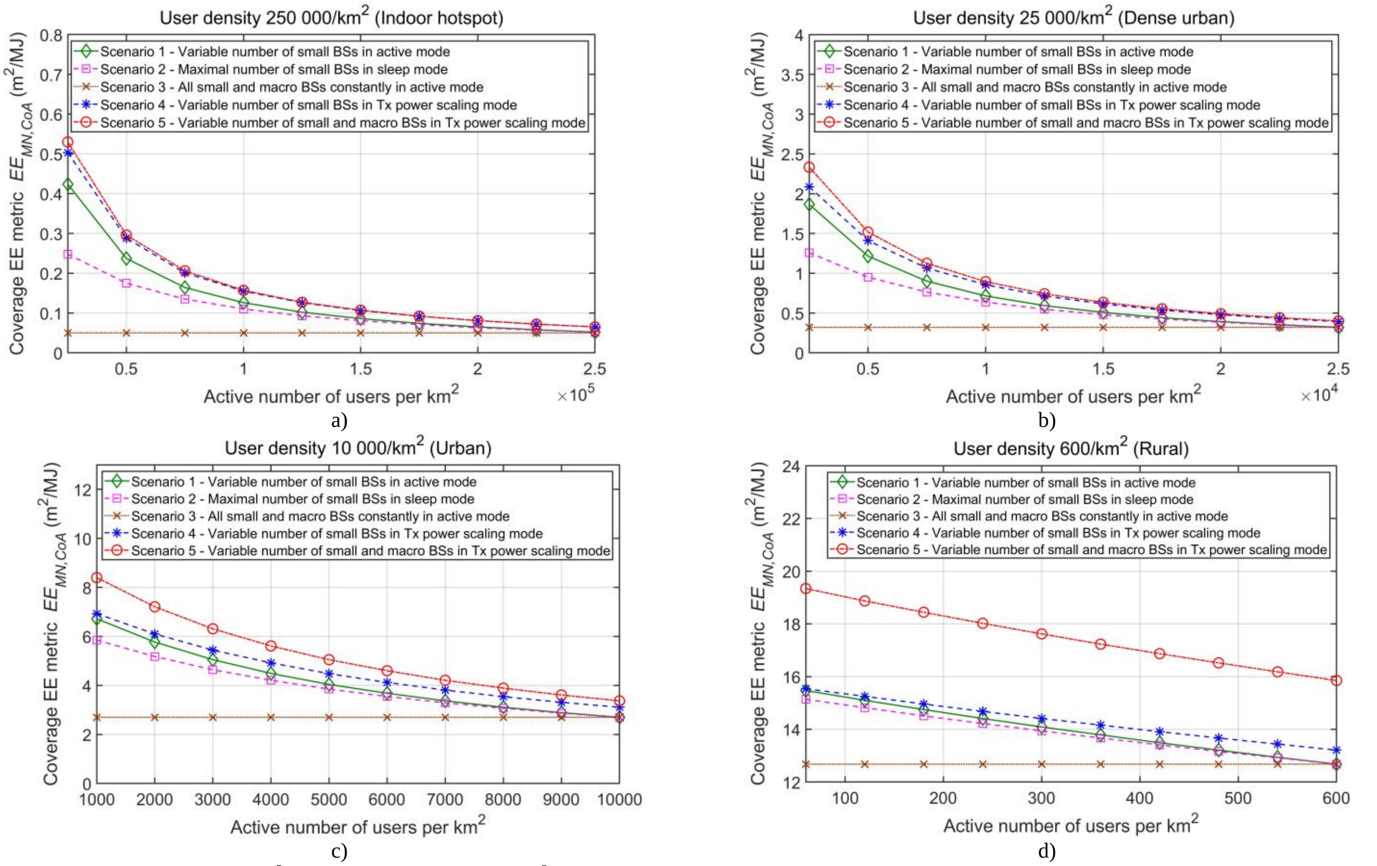

Fig. 3. Coverage EE metric (m^2/MJ) for user density per 1 km^2 in the: a) indoor hotspot scenario; b) dense urban scenario; c) urban scenario and d) rural scenario.

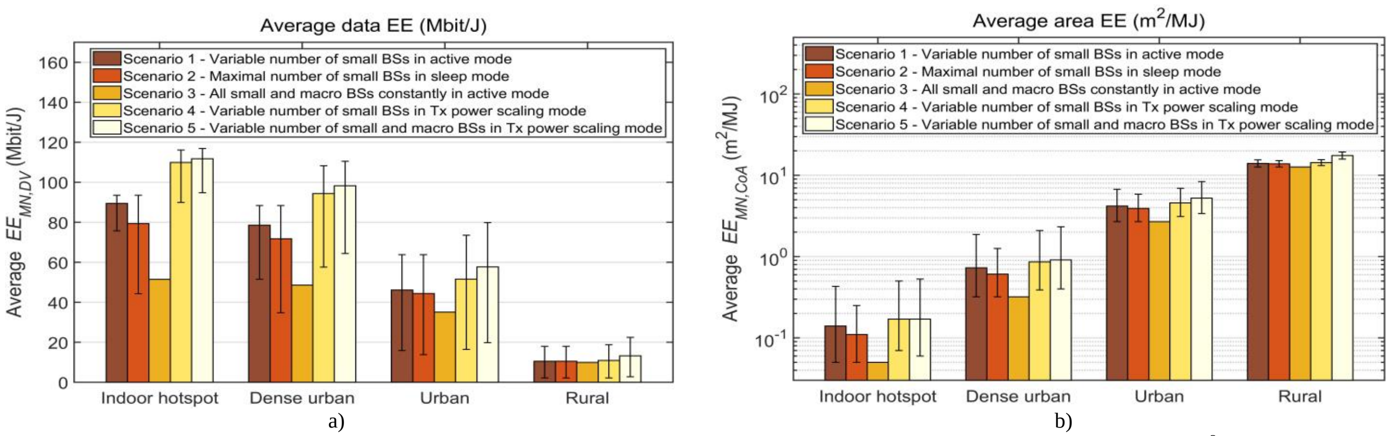

Fig. 4. Average, maximal and minimal trends of different demographic areas for a) data EE metrics (Mbit/J) and b) coverage EE metrics (m^2/MJ)

densities, the power consumption contributed to by the small BSs is lower which results in a better coverage EE metric result for those areas.

According to Fig.3, the coverage EE metric has a monotonic decrease in Scenarios 1, 2, 4 and 5, while Scenario 3 has a constant coverage EE metric for all user densities. As for data EE, the obtained results for coverage EE indicate that Scenarios 1, 2, 4 and 5 offer to the MNOs a better small BSs deployment strategy than legacy Scenario 3, since these scenarios characterize higher average coverage EE (Table III, Fig. 4). The higher average coverage EE of Scenarios 1, 2, 4 and 5 is related to the small BSs deployment and operations strategies used which are performed in accordance with the user density variations and corresponding DVs of the specific demographic areas. In comparison with Scenarios 1 and 2, Scenarios 4 and 5 have a higher average coverage EE (Figs.3 and 4b) due to the exploitation of Tx power scaling which results in an improvement in the overall EC of BSs. In Scenarios 4 and 5, BSs adjust the Tx power according to DV space and time variations which facilitates the optimal EC of the BSs in comparison with the approach in Scenarios 1, 2 and 3 where the BSs transmits constantly at the maximal Tx power level. Hence, in comparison with Scenarios 1, 2 and 3 (Fig.3), the installation and management approach used in Scenarios 4 and 5 can ensure coverage with the 5G HetNet signal of a larger area (in m^2) using the same unit of energy (MJ) for transferring the DV of the same number of active users in any of the analyzed demographic areas.

Therefore from the perspective of coverage EE, the best *allocation strategies of the small 5G BSs* for every demographic area are those performed in Scenarios 1, 4 and 5 (Fig.3). Since the *maximal possible number of installed small BSs is in sleep* mode at any moment, and because small BSs Tx power scaling has been performed according to the variations in traffic DVs, the best small BSs operation strategy for MNO is based on Scenario 4 (Fig.3). Scenario 5 is the best overall small and macro BSs installation and operation strategy in HetNets since it yields the best coverage EE metric for every demographic area and specific DV intensity (Fig.4).

Considering the absolute and average values of the coverage EE metrics shown in Fig.4b, it can be seen that for all simulated scenarios, the highest coverage EE refers to the demographic area with the lowest user density (rural). This is a consequence of the fact that demographic areas with a lower user density require a lower number of small BSs (Table V) which significantly contributes to the decrease in the overall HetNet power consumption and consequently, the coverage EE metric. In comparison with Scenarios 1, 2, 4 and 5, Scenario 3 shows the lowest average coverage EE independently of the user density in a specific demographic area (Fig.3). The reason for this can be found in the constant activity of all BSs initially installed in the hotspot locations of the specific demographic area, and vice versa.

In the case of the highest user densities, according to Fig.3, every graph for every test scenario eventually converges on the minimal coverage EE metric of a specific demographic area (Scenarios 1 - 3 and Scenarios 4 - 5). As in the case of data EE, this is a result of the fact that for the highest user densities in any area, the coverage EE metric cannot benefit from either of the analyzed deployment and operation scenarios since all available HetNet resources must be activated to satisfy the maximal traffic DVs. Additionally, according to Figs.3 and 4b, the distinction in the data EE metrics will be lower for the demographic areas with lower user densities. The reason for this can be found in the lower overall number of active users and corresponding DVs which implies that the usage of a lower number of small BSs will have a lower contribution to the overall HetNet EC in a specific demographic area.

C. Effect of data volume on the energy-efficiency metrics

Besides the influence of user density per km^2 on the EE metrics, the analysis of the impact of the overall DV per km^2 on the EE metrics for the different demographic areas and BSs installation and operation scenarios has been performed. The relationship between total UL and the DL DVs and EE metrics for one square kilometer 5G HetNet area has been modeled by employing numerical analyses based on the interpolation in the Matlab software tool. Matlab 2016 was used for modeling the interpolation functions. For defining how well the proposed interpolation functions fits a set of observations, goodness of fit (GOF) statistical (regression) analyses were performed. The parameters used for the GOF statistical analyses were SSE (sum of squares due to error), R-square, Adjusted R-square and RMSE (root mean squared error). The GOF measures summarize the differences between the obtained simulation values for the data and coverage EE metrics and the values expected under the developed interpolation model.

The results for the proposed interpolation model following the GOF statistical analysis have been presented in Table VI indicating the interpolation (fitting) functions for every analyzed scenario and corresponding demographic area. Every interpolation function in Table VI represents the mathematical expression of the interdependence of the overall DV and specific EE metric. In order to more precisely model each interpolation function for a specific scenario and its corresponding demographic area, power and linear interpolations have been exploited (Table VI).

The R-square and adjusted R-square parameters representing the statistic measures of how successful the fit is when explaining the variation of the data have been obtained for each interpolation function (Table VI). The results of the regression analyses related to the fitting goodness (accuracy) show that the R-square and adjusted R-square parameters range from 99.93 % to 100 %. Additionally, the SSE showing the total deviation of the response values from the fit and RMSE indicating the standard deviation of the residuals (prediction errors) have been also calculated for each interpolation function (Table VI). The obtained results for SSE and RMSE are in the range of $6.409e^{-29}$ - 1.844 and $2.831e^{-15}$ - 0.5132 respectively (Table VI). These regression analysis results confirm the high accuracy of the interpolation functions for modeling the specific interdependence among the DV and data and coverage EE metric points.

Therefore the developed model, based on interpolation functions presented in Table VI, provides an appropriate estimate of the interdependence between the DV of the square kilometer and the EE metrics for the different 5G HetNet installation and operation scenarios. According to Table VI, the EE metrics of the 5G HetNets can be estimated based on the expected traffic DVs for the four demographic areas differing in terms of the density of the user population and for the five installation and operation scenarios. Hence, the proposed interpolation model can be used by MNOs and practitioners during the installation and operation phase for estimating EE in a specific demographic area characterized by the corresponding DVs.

D. Discussion

The presented results in Figs.2 - 4 clearly indicate a strong impact due to the different demographic areas and the number of users in said specific demographic areas on the data and coverage EE metrics of the 5G HetNets. The results presented in Figs.2 and 3 points out the opposite impact of user density on the data and coverage EE metrics in each of the analyzed demographic areas. While an increase in user density in every demographic area has an impact on the increase of the data EE metrics (Fig. 2), it also has an impact on the decrease of the coverage EE metrics (Fig. 3). Such adverse trends in the standardized EE metrics for the different user densities raises considerable deployment and operational challenges for the MNOs. To make the deployment of 5G HetNets as

TABLE VI
INTERPOLATION FUNCTIONS EXPRESSING THE INTERDEPENDENCE OF THE DV AND EE METRICS FOR DIFFERENT DEMOGRAPHIC AREAS AND SCENARIOS

EE metric	Scenario 1-Variable number of small BSs in active mode	Scenario 2 - Maximum number of small BSs in sleep mode	Scenario 3 - All small BSs constantly in active mode	Scenario 4 - Variable number of small BSs in Tx power scaling mode	Scenario 5 -Variable number of small and macro BSs in Tx power scaling mode
Y (x) - Data EE for indoor hotspot area (Mbit/J)	$Y(x) = -4.008*10^4*x^{-0.8718}+96.4$ SSE: 0.008798 R-square: 1 Adjusted R-square: 1 RMSE: 0.03545	$Y(x) = -5608*x^{-0.4917} + 119.5$ SSE: 0.7432 R-square: 0.9997 Adjusted R-square: 0.9996 RMSE: 0.3258	$Y(x) = 0.00165*x$ SSE: 1.564e-05 R-square: 1 Adjusted R-square: 1 RMSE: 0.001398	$Y(x) = -4.729*10^4*x^{-0.8436}+120.8$ SSE: 0.02969 R-square: 1 Adjusted R-square: 0.9999 RMSE: 0.06513	$Y(x) = -5.053*10^4*x^{-0.8729} +120.5$ SSE: 0.0139 R-square: 1 Adjusted R-square: 1 RMSE: 0.04456
Y (x) - Data EE for the dense urban area (Mbit/J)	$Y(x) = -4179*x^{-0.6479} +100.1$ SSE: 0.2433 R-square: 0.9998 Adjusted R-square: 0.9997 RMSE: 0.1864	$Y(x) = -1115*x^{-0.3441} +137.6$ SSE: 1.21 R-square: 0.9995 Adjusted R-square: 0.9994 RMSE: 0.4158	$Y(x) = 0.0101*x$ SSE: 8.784e-05 R-square: 1 Adjusted R-square: 1 RMSE: 0.003314	$Y(x) = -3830*x^{-0.5798} +128.2$ SSE: 0.6053 R-square: 0.9997 Adjusted R-square: 0.9997 RMSE: 0.2941	$Y(x) = -5196*x^{-0.6471} +125.2$ SSE: 0.3785 R-square: 0.9998 Adjusted R-square: 0.9997 RMSE: 0.2325
Y (x) - Data EE for urban area (Mbit/J)	$Y(x) = 333.9*x^{0.05111}- 404.3$ SSE: 1.178 R-square: 0.9995 Adjusted R-square: 0.9993 RMSE: 0.4102	$Y(x) = 47.65*x^{0.1808}- 93.58$ SSE: 1.175 R-square: 0.9995 Adjusted R-square: 0.9994 RMSE: 0.4097	$Y(x) = 0.08509*x$ SSE: 9.954e-05 R-square: 1 Adjusted R-square: 1 RMSE: 0.003527	$Y(x) = 73.84*x^{0.1545}- 131.5$ SSE: 1.555 R-square: 0.9995 Adjusted R-square: 0.9994 RMSE: 0.4713	$Y(x) = 419.6*x^{0.0509}- 507.6$ SSE: 1.844 R-square: 0.9995 Adjusted R-square: 0.9993 RMSE: 0.5132
Y (x) - Data EE for rural area (Mbit/J)	$Y(x) = 1.025*x^{0.7721}- 1.334$ SSE: 0.01598 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.04778	$Y(x) = 0.9262*x^{0.7962}- 1.147$ SSE: 0.01361 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.0441	$Y(x) = 0.4*x$ SSE: 6.409e-29 R-square: 1 Adjusted R-square: 1 RMSE: 2.831e-15	$Y(x) = 0.8004*x^{0.8387}- 0.6811$ SSE: 0.02326 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.05764	$Y(x) = 1.112*x^{0.8032}-1.072$ SSE: 0.04454 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.07976
Y (x) - Coverage EE for indoor hotspot area (m2/MJ)	$Y(x) = 822.9*x^{-0.8695}- 0.008533$ SSE: 3.402e-06 R-square: 1 Adjusted R-square: 1 RMSE: 0.0006971	$Y(x) = 21.41*x^{-0.4866}- 0.05259$ SSE: 9.935e-06 R-square: 0.9997 Adjusted R-square: 0.9996 RMSE: 0.001191	$Y(x) = 0.05$	$Y(x) = 825.1*x^{-0.8484}- 0.01157$ SSE: 8.707e-06 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.001115	$Y(x) = 581.8*x^{-0.805}-0.02311$ SSE: 1.678e-05 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.001548
Y (x) – Coverage EE for dense urban area (m2/MJ)	$Y(x) = 177.1*x^{-0.6494}- 0.1706$ SSE: 0.0004371 R-square: 0.9998 Adjusted R-square: 0.9997 RMSE: 0.007902	$Y(x) = 19.35*x^{-0.3424}- 0.5482$ SSE: 0.0003747 R-square: 0.9995 Adjusted R-square: 0.9994 RMSE: 0.007316	$Y(x) = 0.32$	$Y(x) = 127.9*x^{-0.5795}- 0.276$ SSE: 0.0006595 R-square: 0.9997 Adjusted R-square: 0.9997 RMSE: 0.009707	$Y(x) = 216.3*x^{-0.646}-0.2177$ SSE: 0.0006359 R-square: 0.9998 Adjusted R-square: 0.9998 RMSE: 0.009531
Y (x) - Coverage EE for urban area (m2/MJ)	$Y(x) = -31.04*x^{0.04725} +45.11$ SSE: 0.00877 R-square: 0.9994 Adjusted R-square: 0.9993 RMSE: 0.03539	$Y(x) = -3.146*x^{0.1766}+12.81$ SSE: 0.004277 R-square: 0.9996 Adjusted R-square: 0.9994 RMSE: 0.02472	$Y(x) = 2.7$	$Y(x) = -5*x^{0.1536}+16.91$ SSE: 0.007022 R-square: 0.9995 Adjusted R-square: 0.9994 RMSE: 0.03167	$Y(x) = -35.98*x^{0.0501}+53.47$ SSE: 0.01273 R-square: 0.9995 Adjusted R-square: 0.9993 RMSE: 0.04265
Y (x) - Coverage EE for rural area (m2/MJ)	$Y(x) = -0.1568*x^{0.8034} +16.01$ SSE: 0.000839 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.01095	$Y(x) = -0.1412*x^{0.7995} +15.64$ SSE: 0.0001628 R-square: 1 Adjusted R-square: 1 RMSE: 0.004823	$Y(x) = 12.68$	$Y(x) = -0.1304*x^{0.8067}+16.02$ SSE: 0.0002691 R-square: 1 Adjusted R-square: 0.9999 RMSE: 0.0062	$Y(x) = -0.193*x^{0.8067}+20$ SSE: 0.001041 R-square: 0.9999 Adjusted R-square: 0.9999 RMSE: 0.01219

x – overall data uplink and downlink traffic per km^2 ($Gbit/s/km^2$)

energy-efficient as possible, the MNOs should follow the radio access network deployment strategy which has to be based on the continuous installation of macro and especially small BSs according to a progressive increase of 5G user densities and corresponding traffic DVs during future deployment periods. In addition, to make the operational management of the 5G HetNets as energy-efficient as possible, MNOs should follow the radio resource management strategy which will have to be based on the scheduling Tx power of the small and macro BSs according to space and time traffic DV variations. The widespread legacy approach based on the advanced allocation of a maximal number of constantly powered macro and small BSs, which are capacitated to satisfy the expected future traffic DVs during longer network exploitation periods (of 5 - 10 years), is the approach that is least favorable in terms of both data and coverage EE. Thus, this should be avoided by MNOs.

Another important discussion point refers to the absolute values of the data and coverage EE metrics presented in Figs.2 and 3, and the corresponding maximal, average and minimal values presented in Figs.4. It is worth to emphasize that these absolute and average EE metrics have been obtained for specific HetNet architectures (Table V) composed of different numbers of macro and small BSs. More specifically, the architecture of each analyzed 5G HetNet has been set in terms of the number of macro and small BSs with the goal of satisfying the user density (prescribed by the ETSI standard) and corresponding traffic DVs (also prescribed by the ETSI standard) for the specific demographic area. Obviously, the real practical implementation of 5G HetNets may differ in terms of the user densities and correspondingly, in the number and type of deployed macro and small BSs. For that reason, it is expected that the practical implementation of HetNets can have different absolute and average values for the data and coverage EE metrics. It is also expected that these values in the future will have a decreasing trend in comparison with the EE metric values presented in this analysis. This will be a consequence of the technological advancements made in electronics and the signal processing of macro and small BSs in the future 10 year period. This advancement will result in better spectral efficiency for the lower power consumption of future 5G macro and small BSs which will further contribute to the improvement of the data and coverage EE metric of 5G HetNets [1]. Nevertheless, the average values of the data and coverage EE metrics for a specific demographic area presented in Table V can be used as a benchmark in future analyses and recent HetNet network planning. Furthermore, the trends of the graphs in Figs.2 and 3 presenting the impact of user density in the specific demographic areas for each of the analyzed EE metrics will remain for any HetNet architecture.

An additional discussion remark is related to the assumptions used when performing the analysis presented in this work. The assumption related to ensuring constant DL and UL data rates like those prescribed by the ETSI standard for specific demographic areas (Table II) is hard to expect in practice. In real implementations, the instantaneous UL and DL data rates experienced by users vary primarily according to the available BS capacity, the allocated channel (subcarriers) capacity for the specific user and the signal to noise ratio at the location of the user. However, in comparison with the previous generations of cellular networks, 5G HetNets are envisioned with the goal of ensuring high data throughputs. For that reason, it is reasonable to assume that the expected data rates used in the analysis (Table II) are the average data rates offered to the users at the level of the whole analyzed demographic area.

An additional assumption made in the analysis is related to the decrease of macro and small BSs' instantaneous power consumption by 20% when Tx power scaling is implemented. In reality, the instantaneous power consumption of small and especially macro BSs varies during active BS operations in accordance with the BS load [14]. The power consumption increases when there is an exploitation of a larger amount of BS resources, such as the use of a higher number of transceivers or when a transmission at higher Tx powers take place, and vice versa. It is therefore reasonable to believe that Tx power scaling can reduce the instantaneous power consumption by more than 20% of maximal instantaneous power consumption of the small and macro BSs. This is the most evident in periods when there is no user activity. Hence, it is reasonable to believe that assumption related to reducing the instantaneous power consumption of BSs by 20% of the maximal BSs power consumption is reasonable. The power consumption values used in the analysis (Table II) can thus fairly represent the average power consumption of new generations of macro and micro 5G BSs working in the Tx power scaling mode.

Finally, the performed analyses exclude the impact of BS site power consumption (cooling, ancillary and backhaul equipment) and the power consumption of BSs of other generations (2G/3G/4G), with which most of the macro 5G BS will be collocated. The power consumption of all of these elements undoubtedly affects the data and coverage EE metrics of the cellular network. However, the reason for the exclusion of these elements from the analysis of this work can be found in the primary goal of this paper, which is to show how the differences among the demographic areas and corresponding user density impact the standardized EE metrics of 5G HetNets. This is particularly interesting to MNOs since on the one hand, the radio part of the cellular networks makes the highest contribution to the overall cellular network power consumption and on the other, the extension of cellular networks in the near future will be predominantly realized with 5G BSs.

VI. Conclusion

One of the prime motivations for the deployment of 5G networks is the necessity of accommodating the transfer of constantly increasing DVs. This is primarily caused by an increase in the number of mobile users and corresponding applications. However, the deployment of 5G mobile heterogeneous networks (HetNets) will affect the network EC which will further have an impact on the EE of the radio part of the cellular access network. Hence, this paper has analyzed how the different user densities in versatile demographic areas influence the standardized data and coverage EE metrics of 5G HetNets. Each of the standardized EE metrics have been presented and an analysis is performed for four different demographic areas (indoor hotspot, dense urban, urban and rural) and five different 5G BSs deployment/operation scenarios.

The obtained simulation results indicate a strong impact due to the different demographic areas and the variations in user number in said specific demographic areas on the data and coverage EE metrics of the 5G HetNets. It is shown that an increase in user density causes an increase in data EE metrics and a decrease in coverage EE metrics for each of the analyzed demographic areas. Based on the obtained results, the best 5G small BSs deployment strategy and optimal network operational management strategy have been proposed. The presented results offer general insights into the EE-user density DV trade-off and can be useful to MNOs when pursuing energy-efficient 5G network implementation and operational management for a specific demographic area. Additionally, to estimate the impact of different DVs in a square kilometer area on data and coverage EE, interpolation functions have been developed for each demographic area and analyzed network installation and management scenario. Our future research activity will exploit the results obtained for the average data and coverage EE metrics. These results will be used as benchmark EE metrics in our future research focused on the analysis of larger 5G HetNets with a different share of specific demographic areas in the overall network area at the national level.

References

[1] M. Usama, and M. Erol-Kantarci, "A Survey on Recent Trends and Open Issues in Energy Efficiency of 5G," *Sensors 19*, no. 14: 3126, 2019.

[2] I. Chih-Lin, S. Han, and S. Bian, "Energy-efficient 5G for a greener future," *Nature Electronics*, vol. 3, pp. 182-184, 2020.

[3] F. Jejdling et al., "Ericsson Mobility Report," Ericsson, Stockholm, June 2020.

[4] ITU-R, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," 2015. [Online]. Available: https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf. [Accessed 10 May 2020].

[5] Z. Pi, and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101-107, 2011.

[6] K. Sakaguchi, G. K. Tran, H. Shimodaira, S. Nanba, T. Sakurai, K. Takinami, I. Siaud, E. C. Strinati, A. Capone, I. Karls, R. Arefi, and T. Haustein, "Millimeter-Wave Evolution for 5G Cellular Networks," *IEICE Transactions on Communications*, vol. E98.B, no. 3, pp. 388-402, 2015.

[7] "Telecommunication management; Study on system and functional aspects of energy efficiency in 5G networks (Release 16)," 3GPP, Sophia Antipolis, France, Tech. Rep. 32.972 (V16.1.0) (2019-09), 2019.

[8] ETSI ES 203 228 (V1.2.1) (2017-04), "Environmental Engineering (EE); Assessment of mobile network energy efficiency".

[9] ITU-T L.1331 (04/2017), "Assessment of mobile network energy efficiency".

[10] J. Lorincz, N. Dimitrov, and T. Matijevic, "Bit per Joule and area energy-efficiency of heterogeneous macro base station sites," *SoftCOM 2012, 20th International Conference on Software, Telecommunications and Computer Networks*, pp. 1-6, 2012.

[11] M. M. Mowla, I. Ahmad, D. Habibi, and Q. V. Phung, "A Green Communication Model for 5G Systems," *IEEE Transactions on Green Communications and Networking*, vol. 1, no. 3, pp. 264-280, 2017.

[12] S. Buzzi, C. I, T. E. Klein, H. V. Poor, and C. Y. a. A. Zappone, "A Survey of Energy-Efficient Techniques for 5G Networks and Challenges Ahead," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 697-709, 2016.

[13] P. Frenger, and R. Tano, "More Capacity and Less Power: How 5G NR Can Reduce Network EC," in *2019 IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, Kuala Lumpur, Malaysisa, pp.: 1-5, 2019.

[14] W. Wang, and G. Shen, "Energy Efficiency of Heterogeneous Cellular Network," *IEEE 72nd Vehicular Technology Conference - Fall*, pp. 1-5, 2010.

[15] J. Lorincz, and T. Matijevic, "Energy-efficiency analyses of heterogeneous macro and micro base station sites," *Computers & Electrical Engineering*, vol. 40, no. 2, pp. 330-349, 2014.

[16] E. Björnson, L. Sanguinetti, and M. Kountouris, "Deploying Dense Networks for Maximal Energy Efficiency: Small Cells Meet Massive MIMO," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 832-847, 2016.

[17] ETSI TS 122 261 (V15.5.0) (2018-07), "5G; Service requirements for next generation new services and markets".

[18] H. Holma, A. Toskala, and T. Nakamura, 5G Technology: 3GPP New Radio, John Wiley & Sons, 2020.

[19] J. Lorincz, T. Matijevic, and G. Petrovic, "On interdependence among transmit and consumed power of macro base station technologies", *Computer Communications*, vol. 50, pp. 10-28, 2014.

[20] T. E. Bogale, and L. B. Le, "Massive MIMO and mmWave for 5G Wireless HetNet: Potential Benefits and Challenges," *IEEE Vehicular Technology Magazine*, vol. 11, no. 1, pp. 64-75, 2016.

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