Energy-efficiency analyses of heterogeneous macro and micro base station sites

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Abstract

Due to the introduction of newer technologies like Long Term Evolution (LTE) in already deployed cellular access networks, changes in the energy-efficiency of networks consisting predominantly of macro base station sites (BSSs) can be expected. An investigation has been performed for two prominent energy metrics of cellular networks: Power per Unit Area (PUA) and Energy per bit and Unit Area (EbUA). Analytical relations have been developed that express the influence of parameters such as BSs' transmit (Tx) powers, inter-site distances (ISDs), and a number of heterogeneous macro or LTE micro BSSs on the PUA and EbUA. It has been shown that appropriate selection of these parameters can ensure significant energy savings. Besides the possibility of finding an optimal trade-off among ISDs and Tx powers of macro BSSs, which will minimize PUA and maximize EbUA, adding micro LTE BSs to such heterogeneous networks contributes to the improvement of network energy efficiency.

Keywords: metric, power, energy-efficiency, heterogeneous, wireless, green, base station, design, operator, network

A preliminary version of this paper appeared at the IEEE international conference on Software, Telecommunications and Computer Networks (SoftCOM 2012) on September 11-13, 2012 in Split, Croatia. This version includes further extension of analyses in terms of PUA and EbUA metrics, on cellular network topologies consisted of heterogeneous macro and LTE micro base station sites.

1. Introduction

Over the last decade, services offered by wireless cellular networks have become very popular with consumers. As a consequence, those networks have grown not only in the number of new subscribers and new services, but also in size, which has resulted in increased power consumption. Today, about 3% of electrical energy worldwide is consumed by the information and communication technology (ICT) sector [1]. It is expected that the power consumption of ICT will double every four or five years. Also, ICT has a share of 2% of global CO_2 emissions [2]. In 2008 this corresponded to about 60 billion kWh of electrical energy consumption and about 40 million metric tons of CO_2 [3]. Hence, reducing energy consumption is not only a matter of being "green" and efficient but also important from an economical point of view. This is because a significant portion of the operational expenditures (OPEX) of mobile network operators goes to paying the electrical energy bills [4].

The ever-growing interest in new and reliable telecommunication services has resulted in an increased number of installed base stations (BSs) worldwide. The consequence of a higher number of installed BSs is reflected in higher power consumption of the whole cellular network. Guo at [5] state that BSs have a share in total network power consumption of about 80%. To illustrate how high the power consumption of BSs really is, the authors of [6] found that the ratio of power consumption originating from a mobile station (MS) to that from a BS is 1:150. Such figures motivate the introduction of metrics which will be accepted as indicators of the BSs' energy efficiency. As metrics of the energy efficiency in cellular networks, the Power per Unit Area (PUA) metric measured in [W/km^2] and the Energy per bit and Unit Area (EbUA) metric measured in [bit/J/km^2] receive the highest priority [7], [8]. The different metrics provide dissimilar perspectives on the energy consumption of a radio access network (RAN). Whereas the PUA metric focuses on the total power consumption used to ensure coverage of the specific area, the EbUA metric provides a figure on the bit delivery energy efficiency for a specific area.

Based on these two metrics, it is possible to indicate the influence of a number of neighboring base station sites (BSSs), inter-site distances (ISDs), and transmit (Tx) powers on the energy efficiency of a BSS covering a specific area. Due to the introduction of newer technologies like Long Term Evolution (LTE) in the already deployed cellular access networks, changes in the energy efficiency of a network consisting predominantly of heterogeneous macro base station sites (BSSs) can be expected. This is because macro LTE BSs are generally more energy efficient due to having newer hardware which is less energy demanding. At the same time, such BSs can offer higher transmission rates in comparison with the less energy-efficient BSs of previous technologies like Universal Mobile Telecommunications (UMTS) and the Global System for Mobile Communications (GSM). In addition, the accepted approach in the design of future cellular networks based on combinations of heterogeneous macro and micro/pico/femto LTE BSs raises questions focusing on changes in the PUA and EbUA.

The rest of the paper is organized as follows: Section 2 gives an overview of previous research activity in the area of energy efficiency analyses of wireless access networks. In Section 3, a description of the analyzed heterogeneous network consisting of micro and macro BSSs is given. The power consumption model introduced for LTE micro and heterogeneous macro BSSs is explained in

Section 4. Section 5 contains a description of the radio propagation models used for modeling path-loss characteristics of the analyzed micro and macro BSs. In Section 6, the developed relations for PUA and EbUA are presented and described. The numerical results obtained for each of the analyzed scenarios are thoroughly discussed in Section 7. Finally, some concluding remarks are given in Section 8.

2. Related work

In this section, an overview of the proposed energy-efficient models will be given with a focus on research that considers the PUA and EbUA. Article [9] presents a framework for energy-efficiency evaluation of cellular networks based on a holistic approach through identifying components, links, and networks as the levels that need to be addressed. Due to expectations indicating that the greatest energy savings can be obtained through improvements on the network level, our previous research activity was mainly focused on improving energy efficiency on that level of Wireless Local area Networks [10], [11] and cellular access networks [12]. Additionally, in [13] and [14] the influence of the traffic variations on the power consumption of individual BSs and complete BSSs through continuous measurements performed on different BS technologies installed on that site is analyzed. Based on the measurements obtained, it is possible to perform analyses of PUA and EbUA for BSs of different technologies and production periods.

Furthermore, it is shown in [15] that the concept of the PUA as a system performance metric can be used to obtain power savings. One of the proposed solutions for improving both area and bit-per-Joule energy efficiency is in the deployment of low-power pico BSs combined with the reduction of macro BS transmission power [16]. Power consumption in cellular networks can also be reduced by dividing a large cell into tiers of smaller cells, which saves Tx power by avoiding long-range transmission. This, however, causes strong intra-cell interference, so the authors of [17] proposed three different beamforming techniques to mitigate this interference.

The authors of [18] introduced several models, including bit-per-Joule energy efficiency, to observe BS power consumption under varying ISDs and then coordinate multi-point cooperation (CoMP) technologies. While network densification can improve energy efficiency, the obtained results show that CoMP may in fact lead to decreased energy consumption. The authors of [19] proposed a power consumption model for macro and micro BSs. They concluded that, for conventional macro BS deployments, the ISD of 1500 m is the most energy efficient. The authors of [20] provided a comprehensive survey of techniques dedicated to energy savings in cellular networks and indicated some of the prominent energy-efficiency metrics. In [21], the optimal Tx power and cell radius as well as ISD, which minimizes the PUA of the network with and without the impact of shadowing, were investigated. The authors show that shadowing has a strong influence on the cell coverage area, energy efficiency, and the PUA of macro cell networks. In [22], Fofack used a PUA model to obtain energy savings from cooperating cellular network operators. Paper [23] describes combined LTE macro and micro-cellular heterogeneous wireless network architecture and analyzes its energy efficiency with respect to the variation in ISDs. The results suggest that the deployment of micro cells along with macro cells can improve the energy efficiency of the network as well as provide gains in terms of increased ISD.

The potential deployment of micro BSSs could allow a significant decrease of area power consumption while still achieving certain area-throughput targets as indicated in [24]. In [25], the authors state that the energy savings that could be obtained by combining macro and micro BSs is much higher than that of femto deployment. The authors of [26] evaluated the total BS energy consumption per area for different cell sizes by assuming a certain level of minimum power has been received at the cell edge regardless of cell size. They concluded that, with the high fixed power consumption overhead, the most energy efficient approach is to have as large an ISD as possible. In [27], a new metric, the power consumption per covered area, is introduced, to compare the energy efficiency of different wireless access technologies for a range of bit rates. According to the obtained results, the most energy-efficient technology is UMTS up to a bit rate of 2.8 Mbps, LTE between 2.8 and 8.2 Mbps, fixed WiMAX between 8.2 and 13.8 Mbps, and finally mobile WiMAX for bit rates higher than 13.8 Mbps.

Research activities presented in [21]–[27] do not take into account the fact that in practice cellular operators reuse macro BSSs for allocating newer, fourth generation (4G) BS(s) together with already installed third generation (3G) and/or second generation (2G) BS(s). Such allocation is motivated by financial savings, legislative regulations, and easier installation of new BS technology. According to our knowledge, in article [28] for the first time analyses of the influence of different macro BS technologies installed on the same site on the PUA and EbUA of that site were performed. According to obtained results, PUA mainly depends on the operating frequencies of BS technologies installed on site while Tx power of BSs mainly influences EbUA of the macro BSs site. Also, introducing macro BSs of newer technologies (e.g. LTE) on site contributes to an increase of site EbUA efficiency. However, the analyses performed in [28] do not take into account the heterogeneity of future networks in terms of the allocation of micro LTE BSs along with macro BSSs, as a broadly accepted approach for increasing network throughput. Also, in [28] analyses are performed only for two macro BSSs in order to show the influence of different technologies on the energy efficiency metrics of these sites. Hence, it is necessary to investigate how more than two neighboring BSSs influence the energy efficiency metrics of cellular networks, since real cellular networks contain BSSs surrounded with more than one neighboring BSS. This is why in this paper our analyses have been extended to even more complex cellular networks, which contain a number of heterogeneous macro BSSs and a different number of micro LTE BSs. In addition, different practical scenarios characterized by variations in parameters such as Tx powers, ISDs, and number of neighboring macro and micro BSs have been simulated. Based on the developed relations for expressing PUA and EbUA metrics, the analytical results indicting the influence of the mentioned factors on these metrics are discussed. Also, conclusions regarding energy savings that are useful to the designers of cellular systems are provided.

3. System model

In this paper, analysis is performed for heterogeneous macro and micro BSS(s) allocated in an urban environment. Besides BS racks, a macro BSS contains other networking equipment that is necessary for creating the transport network for BS traffic, like

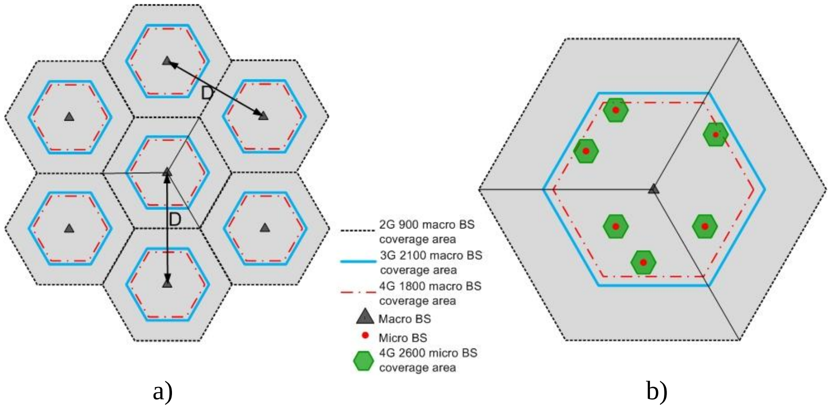


Figure 1. (a) Allocation of reference macro BSS surrounded by neighboring BSSs; (b) allocation of micro LTE BSs inside the coverage area of a macro BSS

Ethernet switches, routers or multiplexers. Although this equipment may contribute slightly to the total energy consumption of the macro BSS, they are not within the focus of our investigations.

According to Figure 1 (a), a macro BSS is defined as an indoor site placed at the center of a hexagonal cell. The *reference* BSS is surrounded by other *neighboring* BSS(s) and contains macro BSs of three different technologies, which are denoted as 2G 900, 3G 2100, and 4G 1800 BSs. Besides the differences in technologies (2G/3G/4G), BSs differ in the corresponding operating frequencies (900 MHz/2100 MHz/1800 MHz). Such a combination of BSs is characteristic for macro sites of the most prominent Croatian mobile network operator and for many other network operators worldwide. In addition, it is assumed that the BS technologies taken into account are typical representatives of the second (2G), third (3G), and fourth (4G) generation of mobile telecommunication systems manufactured in different production periods. Those are GSM, UMTS, and LTE, respectively, and for each analyzed BS technology, corresponding frequencies of 900 MHz, 2100 MHz, and 1800 MHz are commonly exploited in practice.

A typical practical scenario where each macro BS covers three different sectors around the macro BSS with a radiation pattern of 120 degrees per sector is assumed (Figure 1b). In addition, only the downlink direction is considered in the analyses, since downlink coverage defines border area over which service of the BS can be detected by mobile terminals. Since the paper analyses PUA and EbUA, downlink BS coverage is of higher merit then uplink coverage and for that reason it will be used in the further analyses. The analyzed reference site and neighboring BSSs are equal in terms of the number of installed macro BSs, corresponding technologies, and operating frequencies. This is common in practice since BS installed on neighboring sites cover similar or even partially the same areas in terms of morphology and numbers of users. Also, for simplicity it is assumed that all of the macro BSs installed on the same BSS transmit using equal Tx power levels regardless of the applied technology (2G, 3G, 4G). This can be found in many practical scenarios where BSs of different technologies are collocated on BSSs that are used for covering urban environments. This is because significant differences in the Tx power among newly added macro BS technologies (3G or 4G), which operates in similar or higher frequency bands than BS already installed on macro BSS (2G), can influence coverage degradation or interference.

Table 1. Annotation of sets used in mathematical models

Set description	Set index	Set structure
Set of all macro BSs installed on BSS: I	i	$i\epsilon I = \{1, \ldots, M\}$
Set of all micro BSs inside the coverage area of macro BSS: J	j	$j\epsilon J = \{0, \ldots, Q\}$
Set of all macro BS Tx power levels: K	k	$k\epsilon K = \{1, \ldots, Z\}$
Set of all micro BS Tx power levels: U	u	$u\epsilon U = \{1, \ldots, V\}$
Set of all BSs operating frequencies: F	f	$f\epsilon F = \{1, \ldots, P\}$
Set of all neighboring macro sites: S	s	$s\epsilon S = \{0, \ldots, N\}$
Set of all analyzed technologies: T	t	$t\epsilon T = \{1,2,3\}$

Table 2. Macro BS parameters

Parameter	Description	GSM	UMTS	LTE
$N_{sector_{t,f}}$	Number of sectors	3	3	3
$N_{PA_{t,f}}$	Number of power amplifiers per sector	2	2	2
$\mu_{PA_{t,f}}$ [%]	Power amplifier efficiency	15	30	40
$P_{sp_{t,f}}$ [W]	Signal processing overhead	150	110	58
$C_{psbb_{t,f}}$	Battery backup and power supply loss	1.11	1.11	1.11
P_c [W]	Cooling overhead	1000	1000	1000
C_c	Cooling coefficient	1.05	1.05	1.05
$W_{t,f}$ [Hz]	Bandwidth of macro BSs	200×10^3	5×10^6	20×10^6
W_j [Hz]	Bandwidth of micro BSs	/	/	20×10^6
N_0 [W/Hz]	AWGN noise density	4×10^{-21}	4×10^{-21}	4×10^{-21}
	Estimated production year of BS	2001	2009	2013

In order to show the influence of LTE micro BSs on the energy efficiency of such a heterogeneous macro BSS, configurations with different numbers of micro BSs randomly deployed within the coverage area of the heterogeneous macro BSS (Figure 1 (b)) have been considered. Each micro BS is equipped with omni-directional antennas covering a single sector.

In the analyses, a layered approach in terms of areas covered by radio signal around BSSs is assumed. This means that the coverage area of one BS technology represents one independent layer of signal coverage. Since three different types of macro BSs technologies are assumed to be installed on a single macro BSS, three layers of coverage areas specific to the corresponding BS technology will exist around each BSS (Figure 1(a) and (b)). In addition to this, the coverage areas of micro LTE BSs will represent a fourth layer of coverage inside the coverage area of the BSS(s).

3.1 Notation of sets

In order to define the power consumption models and relations for the energy efficiency metrics, a set notation will be used. A list of all sets is given in Table 1. The set of macro BSs installed on each macro BSS is defined as set $i\epsilon I = \{1,2,..,M\}$, where M represents the maximal number of BSs used for a particular analysis. Set $j\epsilon J = \{0,..,Q\}$ indicates the set of micro BSs placed inside the coverage area of the macro BSS. Different Tx power levels of macro BSs ranging from 5 to 40 W in steps of 1 W are defined with the set $k\epsilon K = \{1,2,..,Z\}$. Set $u\epsilon U = \{1,2,..,V\}$ identifies the Tx power levels of micro BSs in Watts ranging from 0.3 to 6.3 W in steps of 0.1 W. The set of parameters dedicated to the specific type of analyzed technology (GSM, UMTS, LTE) is denoted as

Table 3. Maximal instantaneous power consumptions and coverage distances for analyzed macro and micro BSSs

Macro BSs							Micro BS		
P_{Tk} [W]	P_{tot} (GSM) [W]	P_{tot} (UMTS) [W]	P_{tot} (LTE) [W]	d_{GSM900} [km]	$d_{UMTS2100}$ [km]	$d_{LTE1800}$ [km]	P_{Tu} [W]	P_{tot} (LTE) [W]	$d_{LTE2600}$ [km]
5	2282.05	1885.78	1493.01	1.1226	0.5908	0.5805	0.3	33.65	0.1634
10	2515.15	2002.33	1580.42	1.3667	0.7198	0.7067	1	37.5	0.2243
15	2748.25	2118.88	1667.83	1.5335	0.8070	0.7929	2	43	0.2692
20	2981.35	2235.43	1755.24	1.6640	0.8757	0.8604	3	48.5	0.2995
25	3214.45	2351.98	1842.66	1.7728	0.9329	0.9167	4	54	0.3230
30	3447.55	2468.53	1930.07	1.8670	0.9825	0.9657	5	59.5	0.3426
35	3680.65	2585.08	2017.48	1.9505	1.0265	1.0086	6	65	0.3594
40	3913.75	2701.63	2104.89	2.0259	1.0661	1.0475	6.3	66.65	0.3641

$t\epsilon T = \{1,2,3\}$, respectively. The operating frequencies on which the BSs of the analyzed technologies work are indicated with the set of frequencies $f\epsilon F = \{1,2,\dots,P\}$. In general, each macro BS can be expressed as a pair combining elements of the set T and the set F: $i\epsilon(t,f)$. The last set introduced set is a set of all neighboring macro BSSs, $s\epsilon S = \{0,\dots,N\}$, where N represents the number of sites neighboring the reference BSS. For simplicity, in the analyses it is assumed that the ISD between any neighboring macro and reference BSS or any two neighboring macro BSSs is equal to D (Figure 1 (a)). Although in practice allocation of neighboring BSSs may not follow a regular structure with distance D, such an approach is fair approximation, which enables exact mathematical expression of the total area covered by reference and neighboring macro BSSs. According to Figure 1 (a), the maximal number of neighboring BSSs that satisfy these criteria is six.

4. Energy consumption model

4.1. Heterogeneous macro BSS power consumption model

To assess the energy efficiency of the BSS, power consumption models are used for expressing instantaneous power consumption of macro and micro BSSs. Several components have a huge impact on the overall BSS power consumption. Some of them are common for the entire site, and some of them are specific for individual BS technologies. A component that is common for the entire indoor macro BSS is the air conditioner, while the BS-technology-specific component with the highest contribution to the power consumption of the entire BSS is power amplifiers. Also, some components of site power consumption are permanent over time, while others will depend on some parameters such as BS Tx power or traffic load. In this paper, for simplicity, the influence of traffic load on BSS power consumption will be neglected. It is shown in [13] that traffic load has some influence on instantaneous power consumption of BSs, but it should be taken into account that this influence will have a negligible impact on the PUA and EbUA. This is because the PUA and EbUA are dominantly influenced by the size of coverage area, which is significant in comparison with the small variation of instantaneous BSS power consumption caused by daily changes in the traffic pattern intensity.

To evaluate the power consumption of the heterogeneous macro BSS, an instantaneous power consumption model is proposed in the form of:

$$P_{tot_M}(k) = [P_{fix} + P_{var}(k)]C_c + P_c \qquad \text{[W]} \tag{1}$$

In the proposed model, $P_{tot_M}(k)$ denotes the total macro BSS power consumption consisting of M base stations installed on site. It is expressed as the sum of three power consumption components, the variable $P_{var}(k)$, fixed P_{fix}, and cooling P_c components. Variable power consumption $P_{var}(k)$ is a component that scales with Tx power P_{Tk}. It is defined as

$$P_{var}(k) = \sum_{t,f} \frac{K_{t,f}}{\mu_{PA_{t,f}}} P_{Tk} = \sum_{t,f} \frac{K}{\mu_{PA_t}} P_{Tk} \qquad \text{[W]} \tag{2}$$

while P_{fix} is a fixed component, which does not depend on Tx power, and is expressed as

$$P_{fix} = \sum_{t,f} K_{t,f} P_{sp_{t,f}} = \sum_{t,f} K P_{sp_{t,f}} \qquad \text{[W]} \tag{3}$$

A fixed power consumption component takes into account the contribution to the overall power consumption of: signal processing, number and efficiency of power amplifiers, feeder losses, battery backup and power supply loss. In relations (2) and (3), coefficient $K_{t,f}$ is defined as

$$K_{t,f} = K = N_{sector_{t,f}} N_{PA_{t,f}} C_{psbb_{t,f}} \tag{4}$$

where $N_{sector_{t,f}}$ indicates the number of sectors covered by a BS of *t-th* technology transmitting at *f-th* frequency and $N_{PA_{t,f}}$ defines the number of power amplifiers per sector of that BS. Also, $\mu_{PA_{t,f}}$ stands for power amplifier efficiency and $P_{sp_{t,f}}$ is a signal processing overhead. The values of parameters used for expressing coefficient $K_{t,f}$ and other technology-specific parameters can be found in Table 2. The numerical values of these parameters are selected based on references [19], [29] and [30]. As presented in Table 2, analyses is performed using equal numbers of sectors, power amplifiers per sector, battery backup, and power supply loss coefficients ($C_{psbb_{t,f}}$) for each BS technology analyzed and hence $K_{t,f} = K$. Also, for simplicity, the same power amplifier efficiency is assumed in the case when a BS of the same technology operates in a different frequency range and hence $\mu_{PA_{t,f}} = \mu_{PA_t}$. This assumption is due to the fact that power amplifiers of macro BSs of the same technology operating in the different frequency bands are from similar production years and therefore have equal efficiency. Validation of proposed power consumption models for macro and micro BSSs is performed and results are presented in Table 3. It is reasonable to believe that the proposed energy model results in power consumptions, which are characteristic for real macro and micro BSs of corresponding technologies and production periods.

In Relation (1), the contribution of air conditioner power consumption to overall site power consumption is expressed through fixed and variable components. A fixed component which is common for all BS racks installed on the site is denoted as P_c. The variable part of the air conditioner power consumption is expressed in the form of the cooling coefficient by which $P_{var}(k)$ and P_{fix} need to be

Table 4. Parameters of radio propagation models ([32]-[37])

COST-231 Okumura-Hata model Macro BS propagation model		Cost 231 Walfisch-Ikegami model Micro BS propagation model	
Parameter	**Value**	**Parameter**	**Value**
Constant A (150–1000 MHz)	69.55	f (LTE)	2600 MHz
Constant A (1500–2000 MHz)	46.3	Street width w	12 m
Constant B (150–1000 MHz)	26.16	Building separation b	24 m
Constant B (1500–2000 MHz)	33.9	Building heights h_{roof}	20 m
f (GSM)	900 MHz	Base station height h_{BS}	30 m
f (LTE)	1800 MHz	Mobile station height h_{MS}	1.5 m
f (UMTS)	2100 MHz	Street orientation angle φ	30°
Base station height h_{BS}	30 m	Rooftop-to-street diffraction and scatter loss L_{rts}	32.42 dB
Mobile station height h_{MS}	1.5 m		
Correction factor for MS antenna height $a(h_{MS})$	-9.2×10^{-3} dB	L_{bsh}	–18.7451
Area type correction factor C_m	0 dB	k_a	54
Standard deviation/area location probability σ	8 dB/95%	k_f	–1.2838
Slow fading margin *(SFM)*	8.8 dB	k_d	18
MS receiver sensitivity P_R (GSM)	–100 dBm	Standard deviation/area location probability σ	4 dB/95%
MS receiver sensitivity P_R (UMTS)	–102 dBm	Slow fading margin *(SFM)*	3.1 dB
MS receiver sensitivity P_R (LTE)	–100 dBm	MS receiver sensitivity P_R (LTE)	–100 dBm

multiplied. It is important to emphasize that the value of these coefficients depends on the overall number of BS racks installed on the entire site. For the case of the analyzed scenarios containing three macro BSs, the value is equal to 1.05. This kind of scaling is applied because a higher number of BSs working simultaneously on the same site radiates more heat, which results in a higher energy consumption for site cooling.

4.2. Micro BS power consumption model

For estimation of micro BS power consumption, a linear power consumption model, which can be found in [15], [23], [25] and [31], is used. Under the assumption of maximum load, this model can be written as:

$$P_{tot_j}(u) = a_j P_{Tu} + b_j \quad \text{[W]} \tag{5}$$

where $P_{tot_j}(u)$ is total power consumption of the *j-th* micro BS. The power consumption offset b_j is a fixed part of the total BS power consumption, which includes signal processing and power supply consumption of micro BS. Coefficient a_j includes power consumption that scales with Tx power P_{Tu}. According to that, it involves power amplifier losses. Unlike the macro BSS power consumption model, this power consumption model does not take into account cooling losses. That is because micro BSs usually do not require air conditioning. As proposed in [31], the values of a_j and b_j used in this paper are a_j = 5.5 and b_j = 32 W.

5. Propagation model

In this paper, the COST-231 Okumura-Hata path-loss model [32] and the COST-231 Walfisch-Ikegami model [33] are used for modeling the radio channels of macro and micro BSs, respectively. The description and numerical value of each parameter used in these models can be found in Table 4.

By knowing the path loss, calculation of the signal strength $P_R(d)$ detected by a mobile station (MS) located inside the coverage area of the macro BS can be performed according to:

$$P_R(d) = P_{Tk}\ [dBm] - L\ [dB] - SFM\ [dB] \quad [\text{dBm}] \tag{6}$$

Extracting from Relation (6), the maximum coverage distance $d_{t,f}(k)$ in the downlink direction of the *i-th* macro BS transmitting at frequency *f* can be calculated using the relation:

$$d_{t,f}(k) = 10^{\frac{P_{Tk} - P_R - [A + B log_{10} f - 13.82 log_{10} h_{BS} - a(h_{MS}) + C_m] - SFM}{(44.9 - 6.55 log_{10} h_{BS})}} \quad [\text{km}] \tag{7}$$

Similarly, if MS is allocated in the area served by the micro BS, the signal strength $P_R(d)$ that the MS detects from the micro BS can be expressed by the next relation:

$$P_R(d) = P_{Tu}\ [dBm] - L\ [dB] - \text{SFM [dB]} \quad [\text{dBm}] \tag{8}$$

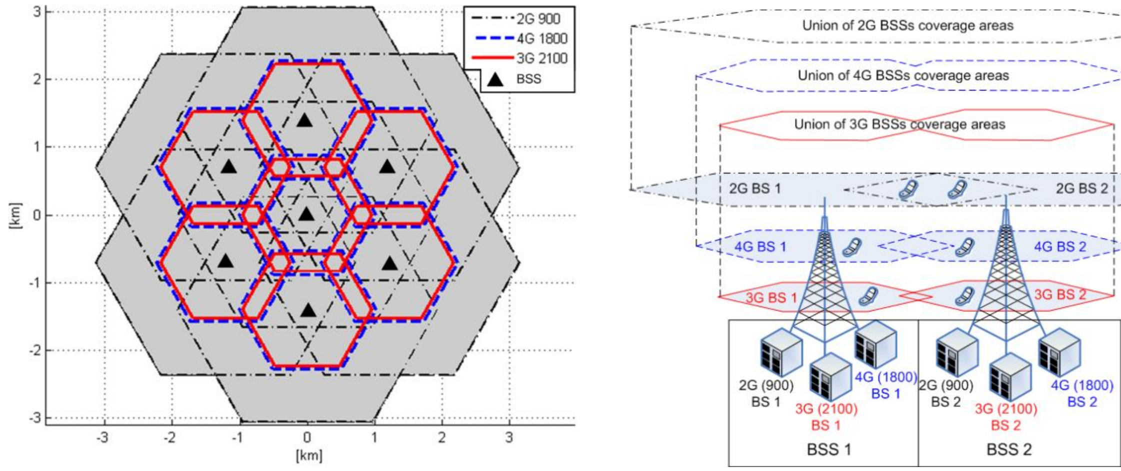
By combining this relation with the path-loss model, the maximum coverage distance $d_j(u)$ in the downlink direction of the *j-th* micro BS can be found according to the relation:

$$d_j(u) = 10^{\frac{P_{tu} - P_R - 32.4 - 20 log_{10}(f) - L_{rts} - L_{bsh} - k_a - k_f log_{10}(f) + 9 log_{10}(b) - \text{SFM}}{k_d + 20}} \quad [\text{km}] \tag{9}$$

Values of MS receiver sensitivities presented in Table 4 have been used according to references [34] and [35]. In a real cellular network, the desired probability of coverage is very high. Because of that, 95% coverage of the macro BSS for each of the analyzed BS technologies have been assumed. For such coverage and standard deviation of σ = 8 dB, which is typical for slow fading in macro cells located in urban areas, the slow fading margin (SFM) value is taken according to [32].

In the case of a micro BS, due to the small distance between the micro BS and the MS, slow fading has a minor impact on the signal transmitted in micro cells. However, it is assumed that micro BSs are placed above rooftop levels and slow fading will have an influence on signal quality. According to that, the SFM value given in Table 4 is selected, which is for a standard deviation of σ = 4 dB and area location probability of 95% taken from [36]. The standard deviation of 4 dB is typical for non-line-of-sight conditions in micro cells. For micro BSs, operating frequency in 2600 MHz band and maximal Tx power of 6.3 W are selected according to [37] and [38], respectively. In Table 3, for different levels of Tx powers, maximal coverage distances calculated based on relations (6) – (9) are presented for macro and micro BSSs.

Maximum coverage distances and corresponding coverage areas of macro BSs are depicted in Figure 2 (a) for different cellular technologies transmitting at the same Tx power level (20 W). Due to the different sensitivity levels of MSs and transmissions in different frequency bands, the coverage areas of BSs transmitting at the same Tx power level will be different. Figure 2 (a) visualizes



a) b)

Figure 2. (a) Coverage areas for BSs of different technologies transmitting at the same Tx power level (b) tridimensional visualization of union of non-overlapping areas for the two neighboring BSSs

the coverage borders of the analyzed macro BS technologies. Additionally, in Figure 2 (b) tridimensional visualization of coverage areas for the case of two neighboring BSSs containing BSs of all analyzed technologies, which transmits at equal Tx powers, is presented.

6. Modeling energy efficiency

6.1. Power per unit area

Generally, Power per Unit Area (PUA) P_A is the energy efficiency metric used for estimating the power consumption of the site relative to its radio signal coverage. In this paper, it is defined as the ratio between the sum of the total macro and micro BSSs' power consumption and the sum of the areas covered by each BS technology installed on a corresponding site. According to Figure 3 (a), (b), and (c), term coverage areas of macro BSs belonging to the specific cellular technology (2G, 3G, 4G) means the union of non-overlapping areas covered by those technologies. Simplified logic considering summation of non-overlapping coverage areas is illustrated in Figure 2 (b). In the calculation of the total coverage area of a specific BS technology, a summation of the non-overlapping unions of areas covered by that technology (Figure 2 (b)) is performed. This is done since each BS of a specific technology serves the traffic demands of MSs connected to that BS by means of the corresponding cellular technology. According to this, the relation P_A for the case when the reference BSS has up to one neighboring macro BSS ($N \leq 1$) and an equal number of micro BSs installed inside the coverage area of the macro BSS(s) can be written as follows:

$$P_A(k,u) = \frac{(N+1)[P_{tot_M}(k)+\sum_j P_{tot_j}(u)]}{[1+N(1-H_{t,f}(k))]\sum_{t,f} A_{t,f}(k)+(N+1)\sum_j A_j(u)} \qquad [\mathrm{W/km^2}] \qquad (10)$$

where H is the overlapping coefficient. This coefficient indicates the percentage of coverage overlapping between neighboring macro

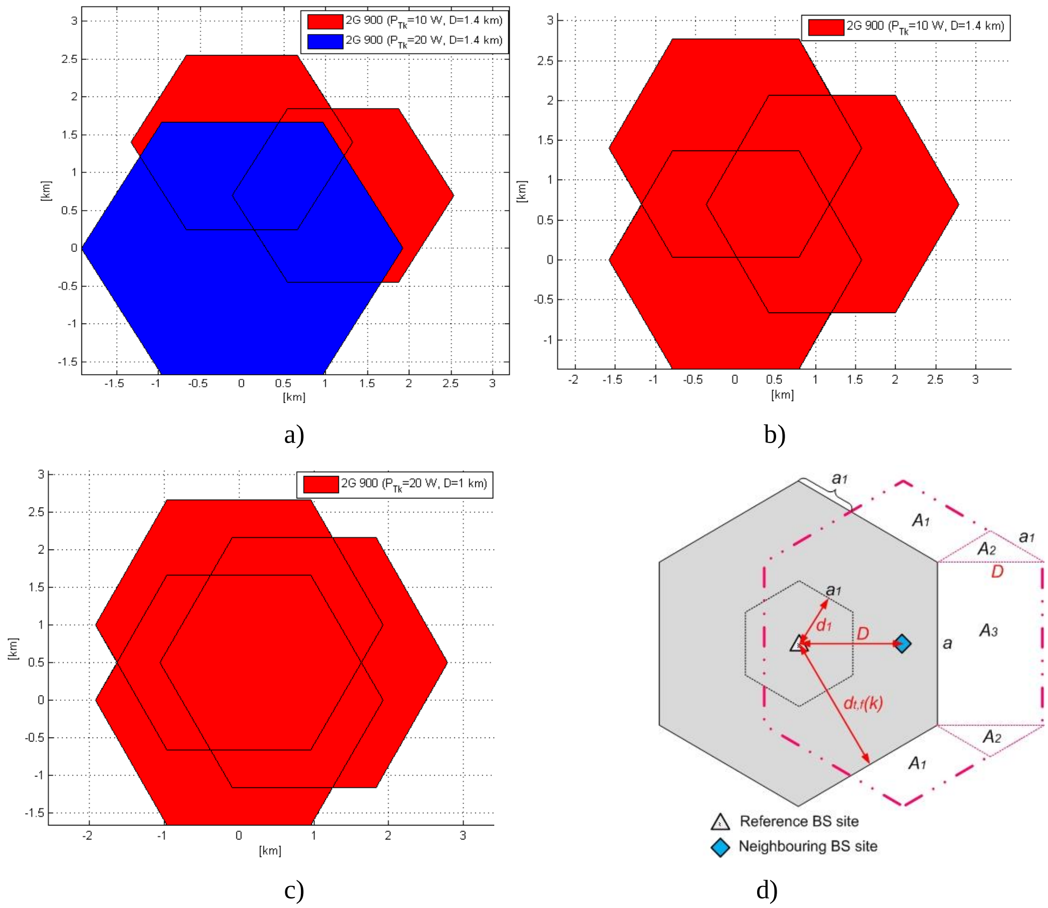


Figure 3. Visualization of coverage overlapping for the case when reference and neighboring BSSs have: a) different Tx powers and fixed ISDs, b) equal Tx powers and fixed ISDs, and c) equal TX powers and variable ISDs. d) Parameters used for calculation of overlapping coverage.

BSs of the corresponding technology. The relation accounts for the case when macro BSs on all BSSs transmit at equal Tx powers. In this case, the level of overlapping illustrated in Figure 3 (d) can be expressed in the next form:

$$H = \frac{A_{t,f}(\mathrm{k}) - 2\mathrm{A}_1 - 2\mathrm{A}_2 - \mathrm{A}_3}{A_{t,f}(\mathrm{k})} = \frac{\frac{1}{6}D^2 - \frac{4}{3}Dd_{t,f}^2(k) + 2d_{t,f}^2(k)}{2d_{t,f}^2(k)} \tag{11}$$

The parameters $A_{t,f}(k)$ and $A_j(u)$ are the areas covered by the *i-th* macro BS transmitting at *k-th* Tx power and the *j-th* micro BS transmitting at *u-th* Tx power, respectively. By knowing the maximum coverage distance of the micro and macro BSs, those areas can be calculated as:

$$A_{t,f}(\mathrm{k}) = 2\sqrt{3}d_{t,f}^2,\ A_j(\mathrm{u}) = 2\sqrt{3}d_j^2 \quad [\mathrm{km}^2] \tag{12}$$

where $d_{t,f}$ represents the diameter ($d_{t,f}$ = *D/2*) of the hexagonal macro cell coverage area (Figure 1 (a)) in the case when the BS of the *t-th* technology transmits at the *f-th* frequency. Similar accounts for diameter d_j of the cell coverage area of the *j-th* micro BS.

In the proposed relation (10), the total consumed power of the BSS is divided by the sum of the unions of the non-overlapping coverage areas of the referent and neighbor BSS and the coverage areas of corresponding micro BS(s). It is worth noting that the PUA as a metric does not sum up; that is, the network level metric is not composed of the sum of the macro and micro BSs level metrics. Relation (10) for calculating P_A can be extended for an arbitrary number of neighboring BSSs ($N \geq 0$) containing M macro BSs surrounded by Q micro LTE BSs and expressed in the form:

$$P_{A_{M,Q}}(k,u) = \frac{\sum_{s=0}^{N} P_{tot_{Ms}}(k) + (N+1)\sum_j P_{tot_j}(u)}{\sum_{i=1}^{M} \bigcup_{s=0}^{N} A_{i,s}(t,f,k) + (N+1)\sum_j A_j(u)} \quad [\mathrm{W/km^2}] \tag{13}$$

where $A_{i,s}(t,f,k)$ is part of the non-overlapping coverage area of the macro BS(s) of the *t-th* technology transmitting on the *f-th* frequency at the *k-th* Tx power. Hence, $\bigcup_{s=0}^{N} A_{i,s}(t,f,k)$ indicates the union of the non-overlapping areas covered by *M* BS(s) of the *t-th* technology. Relation (13) even accounts for the case when, on some BSSs, the *i-th* BS of the same technology *t* as some other BS(s) transmits in different frequency bands. In addition, Relation (13) takes into account the situation where the macro BSs of the *t-th* technology installed on the reference and neighboring macro BSS transmit at different Tx power levels. In this case, the coverage areas and total power consumption of these sites will be different.

In relation (13), total network power consumption is divided with the sum of unions of non-overlapping coverage areas of BSs of *t-th* technology and coverage areas of all micro BSs allocated inside coverage areas of *N* neighboring macro BSSs. According to Figure 2(b)), the union of the non-overlapping coverage areas ($\bigcup_{s=0}^{N} A_{i,s}(t,f,k)$) represents the total coverage area of all BSs of identical technologies. Hence, the left part of the denominator in relation (13) express the sum of non-overlapping coverage areas of each macro BS technology in the network, while the right part takes into account the sum of coverage areas of all micro LTE BSs in the network. This approach is novel and original since it does not sum up individual coverage areas of all BSs of the same technologies (2G, 3G or 4G). Instead, such an approach eliminates multiple summations of those coverage areas over which BSs of equal technologies overlap (Figure 2(b)). Hence, eliminating the influence of multiple summations of overlapped coverage areas on PUA makes this approach more precise and closer to real network implementations.

6.2. Energy per bit and Unit Area

The bit-per-Joule (bit/Joule) energy efficiency is the second energy-efficiency metric considered. According to [16], it is defined as the achievable rate for a unit of energy consumption. Although the total BSS energy consumption and achievable rate individually are the sums of energy consumptions and achievable rates of each BS(s) installed on the BSS, it should be noted that the network level metric (information over energy) is not the sum of corresponding individual metrics of each BS.

In the case of a single BSS, the total achievable rate of BSS is the sum of achievable rates of individual BSs installed on that site. Using Shanon's capacity formula, the overall bit-per-Joule energy efficiency of a single macro BSS and different number of micro BSs allocated inside the coverage area of the macro BSS can be expressed as:

$$EE(k,u) = \frac{\sum_{t,f}\left[W_{t,f}\log_2\left(1+\frac{P_{Tk}}{N_0 W_{t,f}}\right)\right] + \sum_j\left[W_j \log_2\left(1+\frac{P_{Tu}}{N_0 W_j}\right)\right]}{P_{tot_M}(k) + \sum_j P_{total_j}(u)} \quad [\mathrm{bit/J}] \tag{14}$$

In Relation (14), the first part of the numerator defines the total achievable transmission rate of a single BSS consisting of macro BSs transmitting at the *k-th* Tx power level, which can be expressed as:

$$C(k) = \sum_{t,f}\left[W_{t,f}\, log_2\left(1+\frac{P_{Tk}}{N_0 W_{t,f}}\right)\right] \quad \text{[bit/s]} \tag{15}$$

The second part defines the achievable rate of all micro BSs transmitting at the corresponding frequency band using the *u-th* Tx power and is defined as:

$$C(u) = \sum_{j}\left[W_j\, log_2\left(1+\frac{P_{Tu}}{N_0 W_j}\right)\right] \text{[bit/s]} \tag{16}$$

The system bandwidth W defines the transmission speed of symbols over the channel. The coefficient N_0 indicates the power spectral density of the Additive White Gaussian Noise

(AWGN) channel. Values for $W_{t,f}$, W_j, and N_0 used in Relation (14) are given in Table 2 for the analyzed cellular technologies.

As can be noticed from Relation (14), the coverage area of each BS technology was not included as a parameter. This means that the BSs of the same technology transmitting at equal Tx power will have the same bit-per-Joule efficiency regardless of the fact that they can operate in different frequency bands. A possible approach to taking such an effect into consideration is through inclusion of BS coverage areas. In order to relate the bit-per-Joule energy efficiency with the unit area covered by the BS site, a metric called Energy per bit and Unit Area (EbUA) A_{EE} [bit/Joule/km^2] is introduced in [16]. Since the selected metric takes into account coverage areas whose sizes directly depend on the operating frequency of the BSs, the EbUA is considered as a metric in further analyses. In this paper, the EbUA efficiency is identified as the overall bit-per-Joule efficiency per total sum of non-overlapping areas covered by each macro and micro BSS taken into consideration. Therefore, the relation for the EbUA efficiency in the case of up to one neighboring macro BSS ($N \leq 1$) can be expressed as

$$A_{EE}(k,u) = \frac{(N+1)EE(k,u)}{\left[1+N\left(1-H_{t,f}(k)\right)\right]\sum_{t,f} A_{t,f}(k)+(N+1)\sum_j A_j(u)} \quad \text{[bit/J/km}^2\text{]} \tag{17}$$

However, Relation (14) can be generalized for an arbitrary number of neighboring BSSs ($N \geq 0$) containing M macro BSs surrounded by Q micro LTE BSs and expressed in the next form:

$$EE_{M,Q}(k,u) = \frac{\sum_{s=0}^{N} C_s(k)+(N+1)C(u)}{\sum_{s=0}^{N} P_{tot_{Ms}}(k)+(N+1)\sum_j P_{total_j}(u)} \quad \text{[bit/J]} \tag{18}$$

which results in the relation for EbUA defined as:

$$A_{EE_{M,Q}}(k,u) = \frac{(N+1)EE_{M,Q}(k,u)}{\sum_{i=1}^{M}\bigcup_{s=0}^{N} A_{i,s}(t,f,k)+(N+1)\sum_j A_j(u)} \quad \text{[bit/J/km}^2\text{]} \tag{19}$$

As in the case of Relation (13), this relation can also be applied in the cases when BSs of the same or different technologies transmit at

Table 5. Characterization of analyzed scenarios in terms of macro/micro BSs Tx power and ISDs

Scenario	Macro ISD	Tx power of macro reference BS	Tx power of macro neighboring BS	Tx power of micro BS
Scenario 1	Variable (0.2 –3.3 km)	Fixed (20 W)	Fixed (20 W)	/
Scenario 2	Fixed (1.4 km)	Variable (5–40 W)	Variable (5–40 W)	/
Scenario 3	Fixed (1.4 km)	Fixed (20 W)	Variable (5–40 W)	/
Scenario 4	/	Variable (5–40 W)	/	Fixed (2 W)
Scenario 5	Variable	Variable (5–40 W)	Variable (5–40 W)	Fixed (2 W)
Scenario 6	Fixed (1.4 km)	Variable (5–40 W)	Variable (5–40 W)	Fixed (2 W)
Scenario 7	Variable (0.2 –3.3 km)	Fixed (20 W)	Fixed (20 W)	Fixed (2 W)
Scenario 8	Fixed (1.4 km)	Fixed (20 W)	Variable (5–40 W)	Fixed (2 W)
Scenario 9	Fixed (1.4 km)	Fixed (20 W)	Fixed (20 W)	Variable (0.3–6.3 W)

different Tx power levels and have different coverage areas. Also, Relation (19) accounts even for the case when neighboring and reference BSSs differ in the technology, number, and configurations of the installed macro BSs.

7. Numerical results

7.1 Analyzed scenarios

The analyses presented in this paper cover nine different scenarios, each of which simulates a network configuration commonly present in the real cellular networks of mobile operators. In each of them, the Tx power of macro and micro BS(s), the ISDs of macro BSSs, or both, have been adopted. A simplified overview of all analyzed scenarios is given in Table 5.

The analysis is performed in two phases. Firstly, the influence of different numbers of neighboring macro BSSs on the energy efficiency of a reference macro BSS have been analyzed. In this phase, it is assumed that only macro BSSs are situated in the network. The analysis is done for three different scenarios. In Table 5 they are indicated as Scenarios 1, 2, and 3. The approach used in this phase corresponds to the currently most frequently used architectures consisting solely of macro outdoor BSSs.

In the second phase of analysis, the influence of the micro BSs on the energy efficiency of the heterogeneous macro BSSs is analyzed. Such an approach corresponds to future network architectures, which will be dominantly realized as combinations of the heterogeneous macro BSSs and micro/pico BSs. In Scenario 4, only the reference macro BSS and a number of micro BSs allocated inside the coverage area of the macro BSS are considered. In all other scenarios, for simplicity, along with the reference macro BSS, only one neighboring macro BSS ($N = 1$) is included in the analysis. This is because similar conclusions will be obtained even if numbers of neighboring BSSs are higher than one. Scenarios included in this analysis are marked as Scenarios 5–9 in Table 5.

Regarding the last five scenarios, which include the allocation of micro BSs, it is assumed that the same number of micro BSs have been deployed in the coverage area of the reference and neighboring macro BSSs (Q = 2, 4, 6, 8). In order to be as close as possible to the practical implementation, it is assumed that there is no overlapping between coverage areas of micro BSs.

In Scenario 1, BSs installed on the reference and neighboring macro BSSs transmit using a constant Tx power level of 20 W (Figure 3c). The ISD varies from 0.2 km to 3.3 km. The distance of 3.3 km is the maximal coverage distance of macro BSs transmitting at 20 W and operating in the frequency band of 900 MHz. That is the reason why it is selected as the upper limit of ISD.

In Scenario 2, the Tx power on reference and neighboring BSSs changes concurrently from 5 to 40 W (Figure 3b). For all Tx power levels, the ISD is fixed at 1.4 km, which is a typical ISD for macro BSSs placed in urban areas.

In Scenario 3, the ISD is also fixed at 1.4 km. The Tx power of the reference site has a constant value of 20 W while the Tx power of all neighboring sites included in the analyses varies from 5 to 40 W (Figure 3a).

In the fourth scenario (Scenario 4), the influence of macro BS Tx power on energy efficiency metrics in the case of only reference BSSs and a different number of micro BSs have been considered. The macro BSs' Tx power level varies from 5 to 40 W in steps of 1 W and the micro BSs Tx power is fixed at 2 W.

Scenario 5 is dedicated to the analysis of the influence of the ISD on energy efficiency metrics. The Tx power levels of the macro BSs installed on the reference and neighboring BSSs are equal in any moment and concurrently change values from 5 to 40 W. Similarly, the micro BSs' Tx power level is fixed at 2 W. Depending on the macro BSs' Tx power level, the ISD is adopted. For each Tx power level, the ISD is chosen according to the maximal coverage distance of the macro BSs operating at the highest frequency (2100 MHz). This means that the ISD for each Tx power is selected in such a way as to ensure elimination of coverage holes on this frequency, but without coverage overlapping.

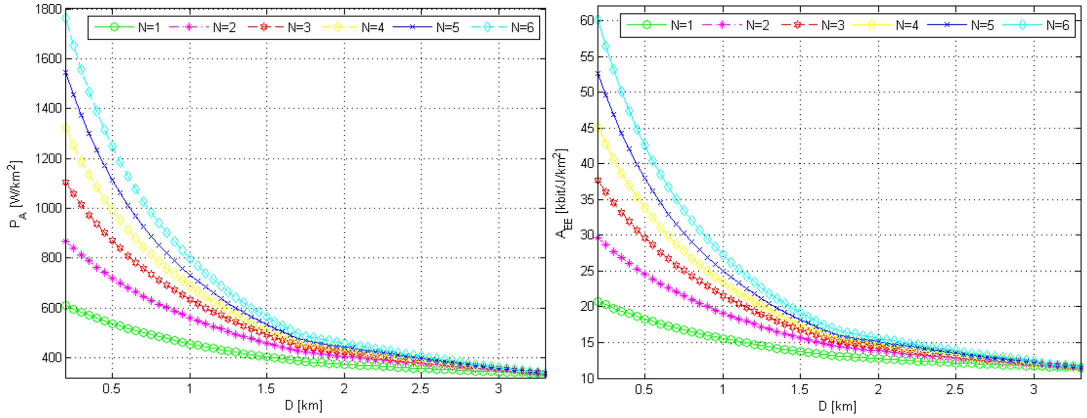
In Scenario 6 the Tx power of the macro and micro BSs accounts the same as in Scenario 5, as the ISD parameter is independent of the macro BS's Tx power. It is fixed at 1.4 km.

In Scenario 7, the Tx power level on the reference and neighboring macro BS sites is fixed at 20 W. As in the previous scenarios, the micro BSs transmit using a constant Tx power of 2 W. The variable parameter is ISD. The maximal analyzed ISD is chosen so that there are no coverage holes between BSs operating at a frequency of 900 MHz. Possible coverage holes between BSs operating at higher frequencies are neglected in this case.

In Scenario 8, the ISD and micro BSs Tx power are the same as in Scenario 6. While the Tx power of the reference macro BSS is fixed at 20 W, the Tx power of the BSs deployed on neighboring macro BS sites changes from 5 to 40 W.

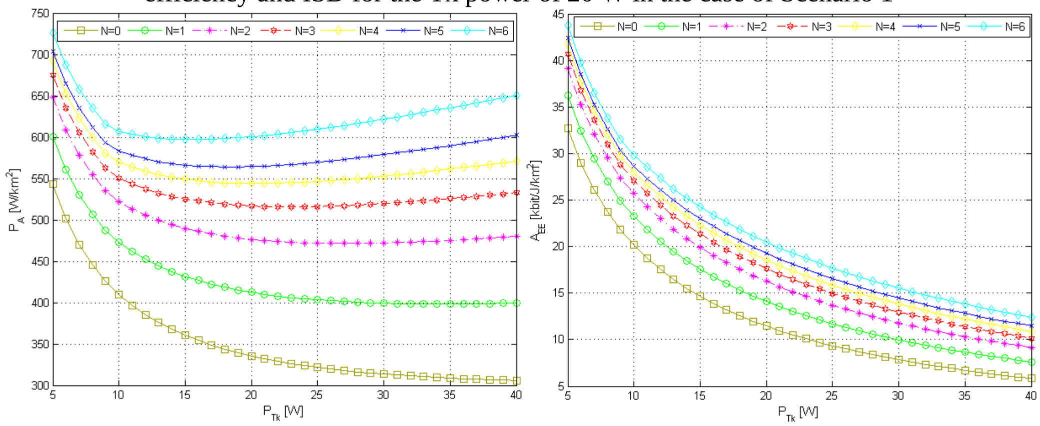
In order to show the interdependence between micro BS Tx power and energy efficiency, in the last analyzed scenario (Scenario 9), the micro BS Tx power has been adopted. At the same time, the ISD and macro BS Tx power are set at constant values of 1.4 km and 20 W, respectively.

Analyses have been performed through simulation of the described scenarios using MATLAB, which enables precise visualization and calculation of non-overlapping coverage areas. Design parameters used as inputs for MATLAB simulation are: locations of macro BSSs, seed number for random generation of micro BSSs, ISDs of macro BSSs, Tx powers of macro and micro BSSs and diameters of hexagonal coverage areas. In total, 391 simulation runs have been performed. More specifically: 63 for Scenario 1, 36 for Scenarios



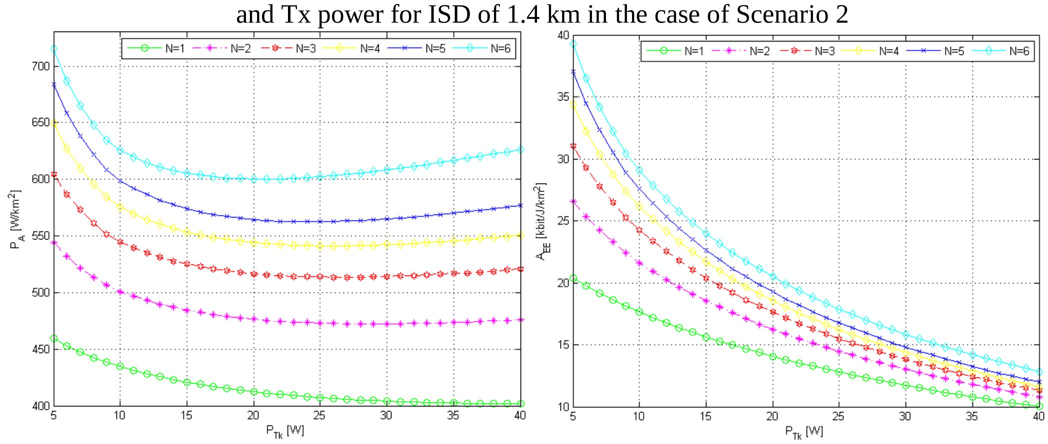
a) b)

Figure 4. (a) Interdependence of the PUA and ISD for Tx power of 20 W in the case of Scenario 1; (b) interdependence of the EbUA efficiency and ISD for the Tx power of 20 W in the case of Scenario 1



a) b)

Figure 5. (a) Interdependence of the PUA and Tx power for ISD of 1.4 km in the case of Scenario 2; (b) interdependence of the EbUA and Tx power for ISD of 1.4 km in the case of Scenario 2



a) b)

Figure 6. (a) Interdependence of the PUA and Tx power of neighboring BSS in the case of Scenario 3; (b) interdependence of the EbUA efficiency and Tx power in the case of Scenario 3

2–6, 63 for Scenario 7, 36 for Scenario 8, and 61 for Scenario 9. The results obtained are discussed in the next subsections.

7.2. Influence of neighboring macro sites on energy efficiency metrics

Figures 4, 5, and 6 present variations of the PUA and EbUA influenced by changes of the BS Tx power or ISD for the case of Scenarios 1, 2, and 3, respectively. Different graph lines on the figures are obtained by placing new neighboring macro BSSs in the simulation. For Scenarios 1, 2, and 3, their position is set so that their coverage areas overlap with the coverage area of the reference macro BSS as visualized in Figure 3 (c), (b), and (a), respectively.

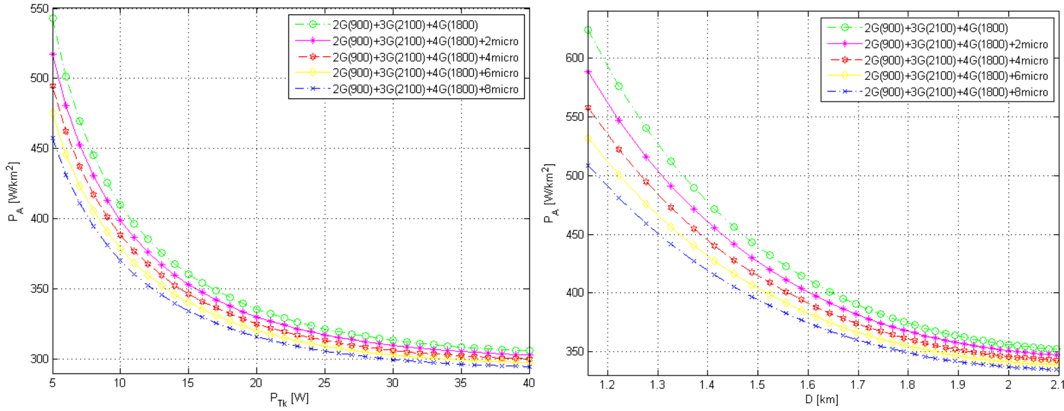
Generally, in Scenarios 1, 2, and 3, the PUA and EbUA increase with deployment of every new BSS. This is because every new BSS contributes to the increase of power consumption and also to the enlargement of the achievable bit rate. However, the PUA and EbUA as metrics have opposite demands. This means that network operators strive towards lower PUA and higher EbUA. Therefore, the best possible trade-off among these two metrics must be achieved.

According to Figures 4, 5, and 6, the largest differences between graph curves presenting the PUA and EbUA values are caused by allocation of the first neighboring BSS (N = 1). With further allocation of BSSs (N = 2–6), those changes become less noticeable with each newly added BSS. This is because the addition of every new BSS contributes to the increase in the number of overlapping layers in those areas where signal coverage of the reference and neighboring BSSs overlap. Since those areas do not contribute to the increase in overall area covered by a group of BSSs, the difference in the PUA and EbUA becomes less discernible.

In the case of Scenario 1, where the ISD changes while the Tx power of the BSSs is fixed at 20 W (Figure 4), the PUA and EbUA decrease with increases in the ISD. Differences in the PUA and EbUA are particularly expressed when neighboring BSSs are placed at lower ISDs (0.2–3.3 km). For ISDs above 2.5 km, the influence of adding a neighboring BSS on the PUA and EbUA is almost negligible. This is due to greater overlapping of the coverage areas of the BSSs with lower ISDs. Since the power consumption of the BSS for the fixed Tx power is assumed to be constant, closer ISDs mean more overlap and consequently higher PUA. This also accounts for the EbUA, which means that EbUA is better for lower ISDs. Therefore, higher values of the EbUA can be expected in areas characterized by higher signal overlapping. The consequence of this is that a higher number of BSs can be detected by the users, which results in the possibility of obtaining the best available bit rate according to the best signal quality detected among different BSs. From the perspective of energy efficiency, the best trade-off for mobile operators in the case of such a practical implementation is an ISD of between 1.5 km and 2 km.

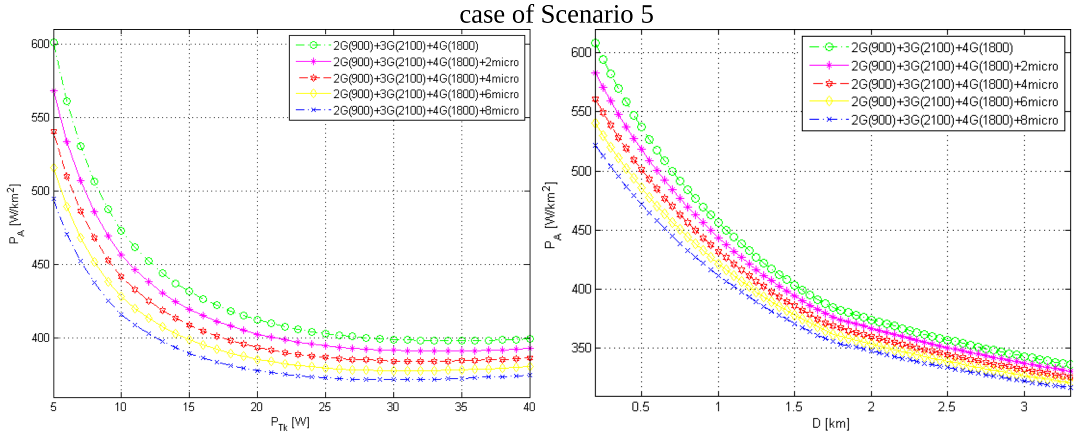
Figure 5 presents the changes in the PUA and EbUA in the case when ISD is fixed at 1.4 km while the Tx power of the BSs installed on the reference and neighboring BSSs varies concurrently (Scenario 2). The results for the PUA and EbUA of Scenario 3 are presented in Figure 6. According to Table 5, differences between Scenarios 3 and 2 can be found in the fixed Tx power (20 W) of the reference BSS.

The parabolic shape of the PUA values presented in Figures 5a and 6a indicates a change in the trend caused by the increase of the Tx power. Up to a certain Tx power, the PUA decreases due to increases in the area covered by BSSs. After that point, the PUA starts to increase since the total BSS power consumption becomes more dominant in comparison with the covered area. On the other hand, Figures 5(b) and 6(b) indicate the hyperbole shape of the EbUA changes. Surprisingly, the increase in the Tx power of macro



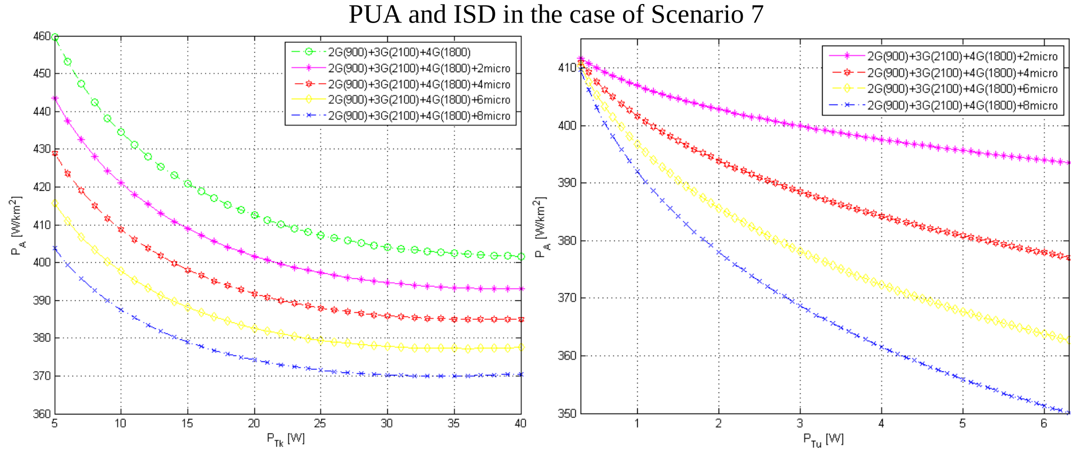
a) b)

Figure 7. (a) Interdependence of the PUA and Tx power in the case of Scenario 4; (b) interdependence of the PUA and ISD in the case of Scenario 5



a) b)

Figure 8. (a) Interdependence of the PUA and Tx power for an ISD of 1.4 km in the case of Scenario 6; (b) interdependence of the PUA and ISD in the case of Scenario 7



a) b)

Figure 9. (a) Interdependence of the PUA and neighboring BSS's Tx power in the case of Scenario 8; (b) interdependence of the PUA and micro BS's Tx power for a fixed ISD in the case of Scenario 9

BSSs will result in a decrease of the EbUA. This is because the higher Tx power results in larger coverage areas, and in order to cover them a higher average energy is needed for transmission of one k/bit. Therefore, mobile operators may find a range of 15 to 20 W to be optimal with regard to energy efficiency in these practical scenarios.

7.3 Influence of micro sites on power per unit area metric

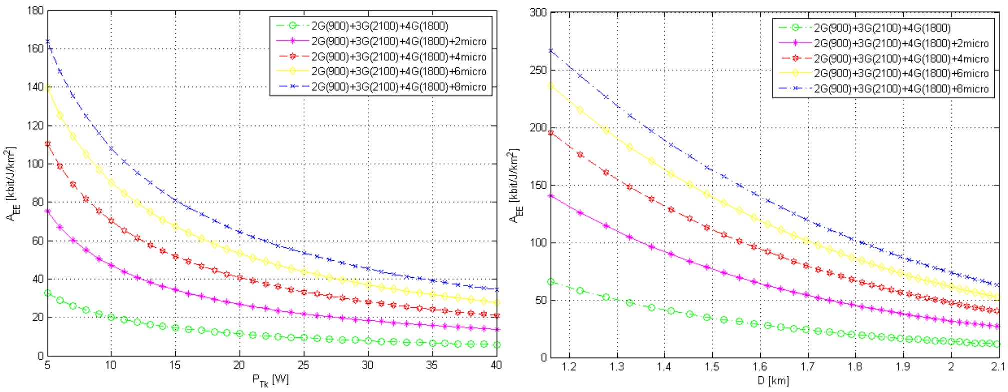
The results indicating variations of the PUA in the case of Scenarios 4, 5, 6, 7, and 8 are presented in Figures 7(a), 7(b), 8(a), 8(b), and 9a, respectively. For these scenarios, it can be noticed that micro LTE BSs transmitting at the constant Tx power (2 W) and allocated in the coverage area of macro BSS have a relatively *small but positive* influence on the PUA of the analyzed heterogeneous cell.

This small influence is a consequence of the dominant impact of the macro BSSs on the overall PUA, due to the significantly lower power consumption and signal coverage of micro BSs in comparison with the power consumption and coverage of heterogeneous macro BSS. Confirmation of this can be found in Figures 7a, 8a, and 9a, which show a parabolic shape of the PUA changes, and in Figures 7b and 8b, which show a hyperbole shape. Actually, the PUA curves for Scenarios 6, 7, and 8 presented in Figures 8a, 8b, and 9a, respectively, are extensions of results which closely follow those obtained for Scenarios 2, 1, and 3, for the case when only one neighboring BSS (N=1) is included in the analysis.

A positive influence means that the covered areas containing heterogeneous macro BSSs and micro LTE BSs have better PUA than those where only heterogeneous macro BSS are deployed (Figures 7, 8, and 9a). This is because deployment of the micro LTE BSs contributes to the creation of one additional layer of coverage, which offers services to users in some frequency bands. More specifically, adding new LTE micro BSs inside the coverage area of the macro BSS results in an additional PUA reduction. This means that from a practical point of view, the introduction of new micro LTE BSs into the already deployed heterogeneous cellular network consisting of the macro BSSs can contribute to the energy-efficiency improvement of an operator’s network. In addition to this, the same PUA indicated in Figures 7 (a), 8 (a), and 9 (a) can be achieved even for the lower values of the macro BSS Tx powers when a number of LTE micro BSs are allocated inside the coverage area of the macro BSS.

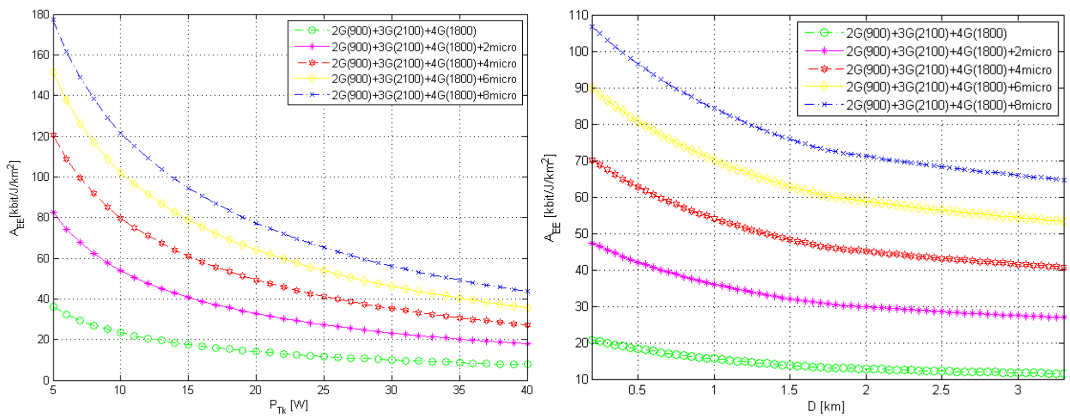
As an example, the Scenarios 6, 7, and 8 can be used for the case when six to eight micro LTE BSs are allocated inside the coverage area of the macro BSSs. This allocation allows network operators to achieve the same PUA if they reduce the Tx power levels of the macro BSSs from the range of 15–20 W to the range of 10–15 W. In urban areas, this cannot significantly degrade coverage quality due to the dense allocation of BSSs, while an additional contribution is made to the energy-efficiency improvement of the BSSs and the whole cellular network.

The results presented in Figure 9 (b) shows that the PUA for Scenario 9 significantly decreases when the micro BS Tx power increases. This is because the increase in the micro BS Tx power makes a higher contribution to the increase in coverage area in comparison with the relatively small contribution to the increase of the micro BS power consumption. According to Figure 9 (b), differences will be more noticeable at higher Tx powers of the micro LTE BSS, since higher Tx powers result in larger coverage areas of micro BSSs. From the perspective of mobile operators, higher Tx powers of LTE micro BSs contribute more to the improvement of network energy efficiency but, on the other hand, the effect of possibly higher interference should be taken into account.



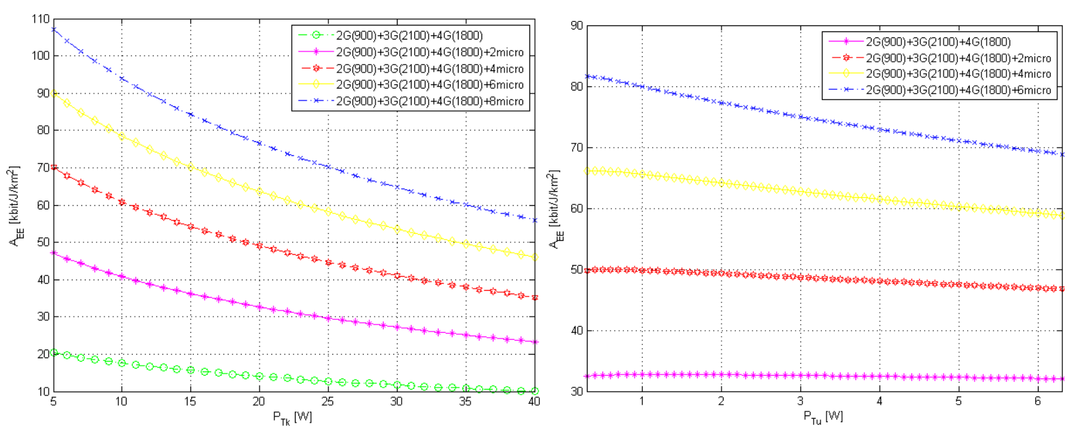
a) b)

Figure 10. (a) Interdependence of the EbUA and Tx power for the case of Scenario 4; (b) interdependence of the EbUA and ISD for the case of Scenario 5



a) b)

Figure 11. a) Interdependence of EbUA and Tx power for the case of Scenario 6; (b) interdependence of area EbUA and ISD for the case of Scenario 7



a) b)

Figure 12. (a) Interdependence of the EbUA and neighboring BSS Tx power for the case of Scenario 8; (b) Interdependence of the EbUA and micro BS Tx power for the case of Scenario 9

7.4 Influence of micro sites on energy per bit and unit area metric

In Figures 10 (a), 11 (a), and 12 (a), the interdependence of the EbUA with macro BSSs' Tx power for different numbers of micro LTE BSs is presented for Scenarios 4, 6, and 8, respectively. In addition, variation of EbUA caused by changes in the macro BSS ISD is shown in Figures 10 (b) and 11 (b) for Scenarios 5 and 7, respectively. Due to the significant influence of macro BSSs on the total EbUA, with an increase of the Tx power or ISD of macro BSSs, EbUA decreases in the case of Scenarios 4 to 8. In fact, the total achievable bit-rate capacity of the operator's network is predominantly fulfilled by the macro BSSs. This is the reason why the shape of the curves in Figures 10, 11, and 12 (a) indicating changes in the EbUA for the case of every new addition of a micro BS closely follows the shape of the curve for scenarios containing only macro BSSs.

Although in the previous subsection it has been shown that allocating new micro LTE BSs makes *some* contribution to the improvement of the PUA, in Figures 10, 11, and 12 (a) a *significant* improvement of the EbUA can be observed in the case of introducing new micro BSs. This is because the introduction of every new micro BS makes a greater contribution to the increase in the achievable bit rate and a smaller contribution to the network energy consumption.

Even for the highest Tx powers (40 W) of BSSs in Scenarios 4, 6, and 8, or for the lowest analyzed ISDs of the BSSs (800 m) in Scenarios 5 and 7, adding micro LTE BSs results in a better EbUA in comparison with those of scenarios containing only macro BSSs. Considering the trade-off between the PUA and EbUA for Scenarios 4, 6, and 8, this further confirms the range of the Tx powers for macro BSSs between 10 W and 15 W in urban areas as optimal for network operators. In addition, the introduction of the micro LTE BSs enables mobile operators to slightly extend ISDs for the case of Scenarios 5 and 7 to a range of between 1.5 and 2 km, in order to reach the optimal trade-off between PUA and EbUA in urban areas. In Figure 12 (b), the influence of the micro BSs Tx power on the EbUA is presented for Scenario 9. The increase of the micro BSs Tx power lowers EbUA due to the larger area that is covered when the micro BSs transmit at higher Tx powers. Figures 9 (b) and 12 (b) shows that the optimal trade-off for network operators in terms of the PUA and EbUA can be found for Tx powers of micro LTE BSs between 2 and 4 W.

Although it was concluded in some of the previous research articles presented in Section 2 that adding LTE micro/pico BSs to the network consisting solely of the LTE macro BSSs has a positive impact on the network's energy efficiency, our results show that this conclusion can be extended to heterogeneous networks. This means that the introduction of the LTE micro BSs has a positive impact on the EbUA and PUA for the already deployed heterogeneous networks of mobile operators consisting of different BSs technologies.

8. Conclusion

This paper aims to show how the BSs' Tx power, ISDs, and number of macro BSSs and micro LTE BSs influence the energy efficiency of cellular network operators. Possible energy savings of a network operator are presented through the analyses of the PUA and EbUA, as the metrics of network energy-efficiency. Results have been obtained based on simulations of many network configurations, which are similar to those in already deployed cellular networks or to those that are expected to be implemented in the future.

Analyses offer information in terms of how to plan and design cellular access networks in order to make them more energy efficient. From the perspective of a cellular network designer, the optimal trade-off regarding the Tx power and ISDs, which contributes to improvements of the energy efficiency of a cellular network consisting only of macro BSSs in urban areas, is estimated. According to the results obtained, Tx power in the range between 15 and 20 W and ISDs ranging from 1.5 to 2 km is the most energy-efficient in such networks. In comparison with those ISDs and Tx power , somewhat higher ISDs and lower Tx powers can be used to achieve the same energy efficiency when a number of micro LTE BSs are installed in the network. This is because deployment of the LTE micro BSs in the operator's network, which consists of heterogeneous macro BSSs, contributes to improvement of the network's PUA and EbUA metrics. By taking into account the results presented in the paper during the design and implementation phase of cellular access networks, operators can achieve energy savings on the level of complete networks. Our further research activities will be focused on the optimal allocation of the micro/pico/femto BSs inside heterogeneous networks of macro BSSs, with the aim being to improve energy efficiency and reduce signal interference.

References

[1] I. Humar, X. Ge and X. Li, "Rethinking Energy Efficiency Models of Cellular Networks with Embodied Energy", *IEEE Network Magazine*, Volume 25, Issue 2, p.p.:40.-49., March-April 2011., doi: 10.1109/MNET.2011.5730527

[2] H. Klessig, A. Fehske and G. Fettweis, "Energy Efficiency Gains in Interference-limited Heterogeneous Cellular Mobile Radio Networks with Random Micro Site Deployment", *Sarnoff Symposium*, May 2011., doi:10.1109/SARNOF.2011.5876468

[3] E. Oh, B .Krishnamachari, X. Liu and Z. Niu, "Toward Dynamic Energy-Efficient Operation of Cellular Network Infrastructure", *IEEE Communications Magazine*, Volume 49, Issue 6, p.p.:56-61., June 2011., doi: 10.1109/MCOM.2011.5783985

[4] C. Han, T. Harrold and S. Armour, "Green Radio: Radio Techniques to Enable Energy-Efficient Wireless Networks", *IEEE Communications Magazine*, Volume 49, Issue 6, p.p.:46.-54., May 2011., doi:10.1109/MCOM.2011.5783984

[5] W. Guo, C. Turyagyenda, H. Hamdoun, S. Wang, P. Loskot and T. O'Farrell, "Towards a Low Energy LTE Cellular Network: Architectures", *European Signal Processing Conference*, p.p.:879.-883., August-September 2011.,

[6] M. Etoh, T. Ohya and Y. Nakayama, "Energy Consumption Issues on Mobile Network Systems", *International Symposium on Applications and the Internet*, p.p.:365.-368., 2008., doi: 10.1109/SAINT.2008.84

[7] M. A. Imran, J. Alonso-Rubio, G. Auer, M. Boldi, M. Braglia, P. Fazekas, D. Ferling, A. Fehske, P. Frenger, R. Gupta, E. Katranaras, S. Manosha, P. Pirinen, N. Rajatheva, D. Sabella, P. Skillermark, L. Van der Perre, A. Vidács, W. Wajda, "Most suitable efficiency metrics and utility functions", *FP 7 EARTH project report, Deliverable D2.4*, January, 2012.

[8] M. W. Arshad, A. Vastberg, T. Edler, "Energy Efficiency Improvement Through Pico Base Stations for a Green Field Operator", *IEEE Wireless Communications and Networking Conference* (WCNC), 2012., doi: 10.1109/WCNC.2012.6214157

[9] L. M. Correia, D. Zeller, O. Blume, D. Ferling, Y. Jading, I. Gódor, G. Auer and L. Van Der Perre, "Challenges and Enabling Technologies for Energy Aware Mobile Radio Networks", *IEEE Communications Magazine*, Volume 48, Issue 11, p.p.:66.-72., November 2010., doi: 10.1109/MCOM.2010.5621969

[10] J. Lorincz, A. Capone, D. Begusic, "Optimized Network Management for Energy Savings of Wireless Access Networks", *Computer Networks Journal*, Volume 55, Issue 3, February 2011., doi: 10.1016/j.comnet.2010.09.013

[11] J. Lorincz, A. Capone, D. Begusic, “Heuristic Algorithms for Optimization of Energy Consumption in Wireless Access Networks”, *KSII Transactions on Internet and Information Systems Journal*, Volume 5, Issue 4, April 2011., doi: 10.3837/tiis.2011.04.001

[12] J. Lorincz, A. Capone, D. Begusic, Impact of Service Rates and Base Station Switching Granularity on Energy Consumption of Cellular Networks, *EURASIP Journal on Wireless Communications and Networking*, 2012:(342), 2012., doi:10.1186/1687-1499-2012-342

[13] J. Lorincz, N. Dimitrov, M. Kapov and G. Petrovic, “Traffic Load Influence on Power Consumption of GSM and UMTS Base Stations”, *Proc. of IEEE International Conference on Software, Telecommunications and Computer Networks (SoftCOM)*, Spetember 2011.

[14] J. Lorincz, T. Garma and G. Petrovic, “Measurements and Modelling of Base Station Power Consumption under Real Traffic Loads”, *Sensors Journal*, Volume 12, Issue 04, p.p.: 4281-4310, 2012., doi: 10.3390/s120404281

[15] F. Richter, A. Fehske and G. Fettweis, “Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks”, *IEEE Vechicular Technology Conference (Fall)*, 2009., doi: 10.1109/VETECF.2009.5379031

[16] W. Wang and G. Shen, “Energy Efficiency of Heterogeneous Cellular Network”, *IEEE Vechicular Technology Conference (Fall)*, 2010., doi: 10.1109/VETECF.2010.5594361

[17] T. Le, S. Nasseri, A. Zarrebini-Esfahani and M. Nakhai, “Power-Efficient Downlink Transmission in Multicell Networks with Limited Wireless Backhaul”, *IEEE Wireless Communications*, Volume 18, Issue 5, p.p.:82.-88., October 2011., doi: 10.1109/MWC.2011.6056696

[18] A. Fehske, P. Marsch and G. Fettweis, “Bit per Joule Efficiency of Cooperating Base Stations in Cellular Networks”, *IEEE GLOBECOM*, p.p.1406.-1411., 2010., doi: 10.1109/GLOCOMW.2010.5700169

[19] O. Arnold, F. Richter, G. Fettweis and O. Blume, “Power Consumption Modeling of Different Base Station Types in Heterogeneous Cellular Networks”, *Proc. of Future Networks and Mobile Summit*, 2010.

[20] Z. Hasan, H. Boostanimehr and V.K. Bhargva, “Green Cellular Networks: A Survey, Some Research Issues and Challanges”, *Communications Surveys & Tutorials, IEEE*, 2011., doi: 10.1109/SURV.2011.092311.00031

[21] A. A. Abdulkafi, S. K. Tiong, J. Koh, D. Chieng, A. Ting, “Energy Efficiency and Cell Coverage Area Analyses for Macrocell Networks”, *International Conference on Future Communication Networks,* 2012, doi: 10.1109/ICFCN.2012.6206866

[22] E. N. Choungmo Fofack, “Cooperative Base Stations for Green Cellular Networks”, *Models for Performance Analysis and Control of Networks (MAESTRO) Project*, February 2010.

[23] T. Tesfay, R. Khalili, J. Le Boudec, F. Richter and A. Fehske, “Energy Saving and Capacity Gain of Micro Sites in Regular LTE Networks: Downlink Traffic Layer Analysis”, *ACM Workshop on Performance Monitoring and Measurement of Heterogeneous Wireless and Wired Networks*, 2011., doi: 10.1145/2069087.2069099

[24] A. Fehske, “Energy Efficiency Improvements through Micro Sites in Cellular Mobile Radio Networks”, *IEEE GREENCOM Workshop*, 2009.,doi: 10.1109/GLOCOMW.2009.5360741

[25] K. Dufkova, M. Popovic, R. Khalili, J. Le Boudec, M. Bjelica and L. Kencl, “Energy Consumption Comparison Between Macro-Micro and Public Femto Deployment in a Plausible LTE Network”, *International Conference on Energy-Efficient Computing and Networking*, p.p. 67.-76., 2011., doi: 10.1145/2318716.2318730

[26] M. Ericson, “Total Network Base Station Energy Cost vs. Deployment”, *IEEE Vechicular Technology Conference (Spring)*, 2011., doi: 10.1109/VETECS.2011.5956433

[27] M. Deruyck, E. Tanghe, W. Joseph and L. Martens, “Modelling and Optimization of Power Consumption in Wireless Access Networks”, *Computer Communications*, Volume 34, Issue 17, p.p.:2036.-2046., March 2011., doi: 10.1016/j.comcom.2011.03.008

[28] J. Lorincz, N. Dimitrov, T. Matijevic, “Bit per Joule and Area Energy-efficiency of Heterogeneous macro Base Station Sites”, *IEEE International conference on Software, Telecommunications and Computer Networks* (SoftCOM 2012), September 11–13, 2012

[29] A. Chatzipapas, S. Alouf, V. Mancuso: “On the Minimization of Power Consumption in Base Stations using on/off Power Amplifiers”, *IEEE Online Conference on Green Communications (GreenCom)*, 2011., doi: 10.1109/GreenCom.2011.6082501

[30] B. Vassilakis, A. Cova, W. Veitschegger: “Wireless base station technology evolution”, *IEEE Compound Semiconductor Integrated Circuit Symposium*, 2004., doi: 10.1109/CSICS.2004.1392468

[31] F. Richter, A. J. Fehske, P. Marsch and G. P. Fettweis: “Traffic Demand and Energy Efficiency in Heterogeneous Cellular Mobile Radio Networks”, *IEEE Vehicular Technology Conference (VTC 2010-Spring)*, 2010., doi: 10.1109/VETECS.2010.5493683

[32] J. Lempiainen, M. Manninen: “Radio Interface System Planning for GSM/GPRS/UMTS”, *Kluwer Academic Publishers*, SAD, 2001.

[33] M. Rahnema: “UMTS Network Planning, Optimization, and Inter-Operation with GSM”, John Wiley & Sons, 2008.

[34] 3GPP TS 25.104 (Release 9), “Base Station (BS) radio transmission and reception (FDD)”, 3rd Generation Partnership Project, 2009

[35] H. Holma, A. Toskala: “LTE for UMTS – OFDMA and SC-FDMA Based Radio Access”, John Wiley & Sons, 2009.

[36] IEEE C802.16-09/0014, IEEE 802.16m Evaluation Results for LBT for IMT-Advanced (input contribution), 24 September 2009, http://ieee802.org/16/docs/#C09_0014

[37] Coletti C., Mogensen P., Irmer R., “Deployment of LTE In-Band Relay and Micro Base Stations in a Realistic Metropolitan Scenario”, IEEE Vehicular Technology Conference (VTC Fall), 2011, pp:1-5, doi: 10.1109/VETECF.2011.6093073

[38] 3GPP TR 25.951 V10.0.0 (Release 10), “FDD Base Station (BS) classification”, 3rd Generation Partnership Project, 2011

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