Bit per Joule and Area Energy-efficiency of Heterogeneous Macro Base Station Sites

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Abstract: **Due to technological development, cellular operators during last decade deploy macro base stations (BSs) of different cellular accesses technologies. Because of a long lifetime of macro BSs spanning over a decade, base stations of the second (2G), third (3G) and fourth (4G) generation can recently be found installed on the same macro base station sites. In this paper, we analyze area consumption and Bit per Joule energy efficiency of such BSs sites composed of 2G, 3G and 4G macro base stations. Analyses have been performed for the case of urban BSs sites, also taking into account BSs of the same technologies working in different frequency ranges. Obtained results show influence of BSs transmitted power and inter-site distance on the area power consumption and area Bit per Joule efficiency.**

1. INTRODUCTION

Over the last decade energy consumed by information and communication technology (ICT) sector has become an important issue. Approximately 3% of the worldwide electrical energy is consumed by ICT [1]. It is expected that energy consumption of the ICT sector will double every four or five years [2]. Since cellular access networks represent a large portion of the ICT sector, impact on energy efficiency caused by adding new BS technologies on already deployed macro BS site is an important issue.

The ever-growing interest in new and reliable telecommunication services has resulted in an increased number of base stations (BSs) worldwide. As a consequence, this increase will result in higher power consumption of the whole cellular network. It is known that power consumption of BSs has a share in total network consumption of about 80% [3]. As metrics of energy efficiency in cellular networks, area power consumption (W/km^2) and Bit per Joule (bit/J) efficiency became widely accepted.

Because of that, we give a brief overview of proposed energy-efficient models with focus on research that considers area power consumption and Bit per Joule efficiency. In [4], authors analyse influence of traffic variations on power consumption of macro site through continuous measurements performed on different BS technologies installed on macro BS site. Authors in [5] introduced several models to observe BS power consumption under varying inter-site distances and coordinate multi point (CoMP) cooperation sizes. It is shown in [6] that the concept of area power consumption as a system performance metric can be used to obtain power savings from the deployment of micro BSs. One of the proposed solution of improving both cell and area energy efficiency is in the deployment of low power pico stations combined with the reduction of macro base station transmission power [7]. According to [8], potential deployment of micro BS sites could allow a significant decrease of the area power consumption in the network while still achieving certain area throughput targets. In [9], authors state that making macro and micro BSs more energy proportional could result in higher energy savings than femto BS deployment. Energy savings in heterogeneous LTE networks can depend on network design decisions like bandwidth allocation schemes, micro BS density and exact positioning of micro BSs in the network [10]. Authors in [11] evaluated the total BS energy consumption per area for different cell sizes by assuming a certain minimum power received at the cell edge regardless of cell size and channel models. They have concluded that with the high fixed power consumption overhead, the most energy efficient way is to have as large inter-site distance as possible. In the frame of EARTH project, a sophisticated power model which maps the RF output power radiated at the antenna elements to the total supply power of a BS site was proposed. Using this framework in the future could lead to significant energy savings by improving energy efficiency of BS at low load [12].

Generally, presented research activities are dedicated to the analyses of the area or Bit per Joule efficiency of some combination of 4G macro and 4G micro/pico/femto BSs. However, in practice cellular operators reuse macro BSs sites for allocating newer 4G BS(s) together with already installed 2G and/or 3G BS(s). Such reuse is motivated with the financial savings, legislative regulations and easier installation of new technology. We exploit this fact in analyses presented in this paper. According to our knowledge, this is the first paper that takes into account influence of different macro BS technologies installed on site on the area and Bit per Joule energy efficiency of that site.

The rest of the paper is organized as follows: in Section 2, propagation model used for coverage estimation of analyzed BSs technologies is presented. Section 3 explains the proposed model of site power consumption. In addition, definition of area and bit per Joule energy efficiency is given in Section 4. In Section 5, obtained results in terms of area and Bit per Joule efficiency are discussed. Section 6 eventually concludes the paper.

2. PROPAGATION MODEL

For modelling the radio channel of a given cellular technology we used COST-231 Okumura-Hata path-loss model for macro BSs. We have assumed urban morphology,

Table 1. Parameters of Okumura-Hata (Cost-231) propagation model

Parameter	Value
Constant A (150-1000 MHz)	69.55
Constant A (1500-2000 MHz)	46.3
Constant B (150-1000 MHz)	26.16
Constant B (1500-2000 MHz)	33.9
f (LTE)	800 MHz
f (GSM)	900 MHz
f (GSM/LTE)	1800 MHz
f (UMTS)	2100 MHz
f (LTE)	2600 MHz
Base station height h_{BS}	30 m
Mobile station height h_{MS}	1.5 m
Correction factor for MS antenna height $a(h_{MS})$	$-9.2\text{x}10^{-3}$ dB
Area type correction factor C_m	0 dB
Slow fading margin SFM	8.8 dB
Standard deviation/area location probability σ	8 dB/95%
BS receiver sensitivity P_R (GSM)	-104 dBm
MS receiver sensitivity P_R (GSM)	-100 dBm
BS receiver sensitivity P_R (UMTS)	-106 dBm
MS receiver sensitivity P_R (UMTS)	-102 dBm
BS receiver sensitivity P_R (LTE)	-102 dBm
MS receiver sensitivity P_R (LTE)	-100 dBm

which is the most demanding in terms of radio propagation environment. COST-231 Okumura-Hata formula is given by

$$L = A + Blog_{10}f - 13.82log_{10}h_{BS} - a(h_{MS}) \\ +(44.9 - 6.55log_{10}h_{BS})log_{10}d + C_m \quad [dB] \qquad (1)$$

where f is a frequency of a given technology and d is the distance between the mobile station (MS) and BS. Description and numerical values of each parameter used in relation (1) can be found in Table 1.

Mobile antenna correction factor $a(h_{MS})$ is given by

$$a(h_{MS}) = 3.2\left(log_{10}(11{,}75h_{MS})\right)^2 - 4.97 \quad [dB] \qquad (2)$$

By knowing path-loss, calculation of the signal strength $P_R(d)$ received at the position of MS allocated in urban area has been performed according to

$$P_R(d) = P_{Tk}\,[dBm] - L\,[dB] - SFM\,[dB] \quad [dBm] \qquad (3)$$

In relation (3), P_{Tk} stands for total transmit (Tx) power radiated from BS antenna, while SFM stands for slow fading margin. Extracting from relation (3), maximum coverage distances in uplink and downlink directions of BSs allocated inside urban area are calculated using relation

$$d_{urb} = 10^{\frac{P_{Tk}-P_R-C-SFM}{(44.9-6.55log_{10}h_{BS})}} \quad [\text{km}] \qquad (4)$$

where C is equal to

$$C = A + Blog_{10}f - 13.82log_{10}h_{BS} - a(h_{MS}) + C_m \text{ [dB]} \qquad (5)$$

In Table 1, constants A and B of COST-231 Okumura-Hata path-loss model are different for different range of frequencies [13]. For the calculation of SFM we have used area location probability, which for standard deviation of σ = 8 dB and area location probability of 95% can be calculated according to the normal Gaussian distribution. Since the desired probability of coverage is very high in real cellular networks, 95% coverage around BS site for each of analyzed technologies has been assumed. BS and MS receiver sensitivities have been used in compliance with ETSI and 3GPP standards [14], [15]. According to used propagation model, macro BSs transmitting at the same Tx power level on different frequencies will have different coverage areas (Figure 1).

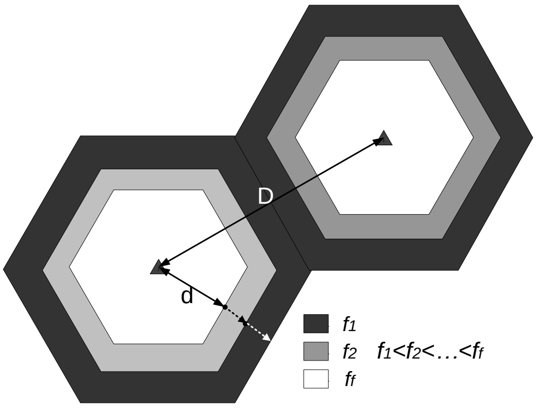

Figure 1. Interdependence of BS site coverage area and frequency for the same Tx power

3. POWER CONSUMPTION MODEL

In the performed analyses we assume different combinations of macro BSs in terms of number of installed BS on the same site. Also, we take into account combinations of different BSs technologies like:

- Global System for Mobile Communications (GSM),
- Universal Mobile Telecommunications System (UMTS),
- Long Term Evolution (LTE) with corresponding frequencies on which they can work.

In addition, each installed BS covers three different sectors around BS site, with radiation pattern of 120 degrees per sector. It is also assumed that each BS has two power amplifiers per sector (Table 2). Such assumptions are typical for nowadays macro BS sites.

On a BS site there are several components with huge impact on overall site power consumption. These components can be divided in two groups; first is group of individual BS technology dependent components and second is group of components common for entire site. Power amplifier belongs to the first group, as component with highest contribution in the power consumption of BS. As for the second group member, the same counts for air conditioner. Knowing this, it is necessary to use appropriate power consumption model which includes influence of all components, especially those before mentioned.

For modelling power consumption of entire BS site, we define few sets. With set $i\epsilon I = \{1,2,..,M\}$ we define the set of all BSs installed on site, where M represents maximal number of BSs used for a particular analysis. Set $k\epsilon K = \{1,2,..,Z\}$ defines transmit power levels in Watts ranging from 5 W to 40 W in steps of 1 W. It is assumed that each

Table 2: Explanation of base station 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 (1.05)	1 (1.05)	1 (1.05)
$W_{t,f}$ [Hz]	Bandwidth	200×10^3	5×10^6	20×10^6
N_0 [W/Hz]	AWGN noise density	4×10^{-21}	4×10^{-21}	4×10^{-21}

macro BS installed on site transmits using the same Tx power level. Set of parameters dedicated to specific type of analysed technology (GSM, UMTS, LTE) is defined as $t\epsilon T = \{1,2,3\}$. Last set that we introduce is the set of frequencies $f\epsilon F = \{1,2,\dots,P\}$ indicating operating frequencies on which BSs of the analysed technologies work.

Each BS *i* is expressed as pair combining elements of two sets; the set *T*, defining specific BS technology and the set *F* indicating frequency on which this BS operates: $i\epsilon(t,f)$. Values of technology specific parameters (summarized in Table 2) are taken into account according to references [16], [17], [18].

This paper employs linear instantaneous power consumption model in the form of:

$$P_{total_M}(k) = [P_{fix} + P_{var}(k)]C_c + P_c \qquad \text{[W]} \qquad (5)$$

According to this model, $P_{total_M}(k)$ is the total site power consumption consisted of *M* base stations installed on site. Site consumption is expressed as sum of three power consumption components, $P_{var}(k)$, P_{fix} and P_c. $P_{var}(k)$ is variable power consumption component that scales with Tx power P_{Tk}

$$P_{var}(k) = \sum_{t,f}\frac{K_{t,f}}{\mu_{PA_{t,f}}}P_{Tk} \qquad \text{[W]} \qquad (6)$$

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

$$P_{fix} = \sum_{t,f}K_{t,f}P_{sp_{t,f}} \qquad \text{[W]} \qquad (7)$$

In relations (6) and (7), coefficient $K_{t,f}$ is defined as

$$K_{t,f} = N_{sector_{t,f}}N_{PA_{t,f}}C_{psbb_{t,f}} \qquad (8)$$

and values of parameters used for expressing coefficient $K_{t,f}$ can be found in Table 2. According to Table 2, we perform analyses using the same number of sectors, power amplifiers per sector and cooling coefficients for the case of each BS technology and hence $K_{t,f} = K$. Also, for simplicity we assume the same power amplifier efficiency in case when BS of the same technology operates in different frequency range $\mu_{PA_{t,f}} = \mu_{PA_t}$.

Finally, in relation (5) P_c is a fixed part of power consumed by air conditioner and it is common for all BS racks installed on the site. The variable part of air conditioner power consumption is expressed in the form of cooling coefficient by which $P_{var}(k)$ and P_{fix} need to be multiplied. It is important to emphasize that value of these coefficient depends on number of BS racks installed on the entire site and according to this it has value of 1 if there is one or two BS(s) on the site or 1.05 if there is three or more BSs. This kind of scaling is applied because greater number of BSs working simultaneously on the same site radiates more heat, what results with more energy consumed for site cooling.

4. AREA AND BIT PER JOULE EFFICIENCY

In order to estimate the power consumption of the site relative to its radio signal coverage, site area power consumption (P_A) is used as criteria. It can be defined as ratio between total BS site power consumption and sum of the areas covered by each BS installed on site. According to this, the relation for P_A can be written as:

$$P_{A_M}(k) = \frac{(N+1)P_{total_M}(k)}{[1+N(1-H)]\sum_{t,f}A_{t,f}} \qquad \text{[W/km}^2\text{]} \qquad (9)$$

where *N* is the number of neighbouring BSs sites and *H* is the overlapping coefficient which indicates percentage of coverage overlapping with neighbouring BS(s) sites. The $A_{t,,f}$ is the area covered by *i-th* BS that can bi calculated as:

$$A_{t,f} = 2\sqrt{3}d_{t,f}^2 \qquad \text{[km}^2\text{]} \qquad (10)$$

where $d_{t,f}$ stands for maximum coverage distance of *t-th* BS working at frequency *f* calculated according to COST-231 or Okumura-Hata propagation model. It is the BS operating frequency dependent parameter in terms that transmitting on some Tx power with lower frequency means larger coverage (Figure 1). For simplicity, in our analyses we neglect influence of inter-cell interference among neighbouring BSs sites.

The second metric for site energy-efficiency considered in this paper is Bit per Joule efficiency which is, according to [19], defined as the achievable rate for unit of energy consumption. Using Shanon's capacity formula, overall Bit per Joule efficiency of analyzed BS site can be expressed as:

$$EE_M(k) = \frac{\sum_{t,f}W_{t,f}log_2(1+\frac{P_{Tk}}{N_0W_{t,f}})}{P_{total_M}(k)} \qquad \text{[bit/Joule]} \qquad (11)$$

where relation in numerator defines sum of total achievable transmission rates of all BSs installed on the site. How fast symbols can be transmitted over the channel depends on the system bandwidth $W_{t,f} = W_t$. Coefficient N_0 stands for the power spectral density of Additive white Gaussian noise (AWGN) channel. Values used for both, $W_{t,f}$ and N_0, are given in Table 2.

As it can be seen, relation (11) doesn't involve frequency as direct coefficient, what means that the maximum coverage areas of BSs can not be taken into consideration. In order to relate Bit per Joule energy efficiency with unit area covered by BS site, metric called area Bit per Joule energy efficiency [bit/Joule/km^2] is introduced in [7]. By knowing this fact, area Bit per Joule energy efficiency will be used as metric in further analyses. This is because selected metric gives more precise information about energy efficiency of macro BS site.

In our case, it is identified as overall Bit per Joule energy efficiency per total sum of areas covered by each base station taken in consideration. Therefore, relation for area Bit per Joule energy efficiency can be written in the form of

$$A_{EE_M}(k) = \frac{(N+1)EE_M\,(k)}{[1+N(1-H)]\sum_{t,f} A_{t,f}} \qquad [\text{bit/Joule/km}^2] \qquad (12)$$

In case of using area Bit per Joule efficiency as the metric, it is possible to take into account energy efficiencies of the same BS technologies transmitting at different frequencies (e.g. LTE 800 and LTE 2600).

5. RESULTS AND ANALYSIS

Analyses have been performed in order to find how BSs Tx power and inter-site distances influence on the area and Bit per Joule power consumption of different macro BSs sites. We assume that two neighbour macro sites are equal regarding number of installed macro BSs and corresponding technologies. Also we assume that all macro BSs installed on site, regardless of used technology transmit using equal Tx powers. This scenario can be found in many practical implementations where two neighbour macro BSs sites have equal BSs, all transmitting at the same Tx power.

5.1. Area power consumption

According to the obtained results presented in Figures 2 and 3, it can be seen that increase in both, the Tx power and inter-site distance, results with decrease in the area power consumption (APC) of macro BSs site. This conclusion worth's for each of BSs site combinations since higher Tx power results in higher coverage area of each BS technology. But, further increase in BSs Tx power above 40 W, although not presented on Figure 2, is followed with increase in overall site power consumption. This consequently results with increase of APC (P_A). Therefore, best results in terms of APC are obtained for the Tx powers between 20 W and 40 W.

However, influence on the APC of newly installed BSs on macro site, significantly depends on operating frequency of added BS (Figures 2 and 3). In order to eliminate coverage holes between two macro sites, results presented in Figure 3 are obtained for coefficient of macro site overlapping H calculated for highest frequencies ([D(2600)], [D(2100)]) of analysed combinations. Therefore, for the same Tx power or inter-site distance, combinations of BS technologies working dominantly at lower frequencies have better APC in comparison with sites having BS technologies dominantly working in the higher frequency bands.

As an interesting example presented in Figures 2 and 3, we emphasize sites having 4 BSs, differing only in the operating frequency of LTE BS (2.6 MHz or 0.8 MHz). By adding to the existing macro site the LTE BS working in the lower frequency band, significant improvement in terms of APC can be achieved.

Figure 4 presents changes in the APCs for different Tx powers, in case of inter-site distance fixed on 1.4 km. This inter-site distance is typical for urban areas. Due to multiple coverage overlapping incurred by the two identical neighbouring macro BSs sites, the APC is higher in comparison with the single macro BSs site (Figure 2) even for the lowest levels of the Tx power. As in the case of single macro BS site presented in Figure 2, increase in the Tx power results with changes of the APC having parabolic shape. This means that for each combination of macro BSs, APC of macro sites decreases up to some value of Tx power, after which starts to increase since macro site power consumption becomes dominant. Higher values of the APCs are obtained for such BS combinations having more BSs transmitting at higher frequencies. This is because higher frequencies at the same Tx power ensure lower coverage areas and consequently such BSs combinations will have higher APCs.

Similar but more linear trend of APC changes can be noticed in Figure 5. We analyse influence of the inter-site distances on the APC in case when all BSs transmits at fixed Tx power typical for today's macro BSs (20 W). In this example, we express inter-site distance D (Figure 1) as function of referent coverage area, obtained at the selected Tx power level (20 W) for BS technology operating at frequency of 900 MHz. Therefore, we manage to express percentage of macro sites overlapping H as function of inter-site distance D and maximal site coverage d (Figure 1).

In case when each BS of two macro sites transmits at equal Tx power (20 W), the APC decreases when inter-site distance increases. This is consequence of reduced coverage overlapping, where extending inter-site distance results with lower overlapping. Actually, at some fixed Tx power, for the lower level of macro sites overlapping, the lower APC will be.

5.2. Area Bit per Joule efficiency

In Figures 6, 8 and 7, 9, area Bit per Joule energy-efficiency (AEE) is presented for different Tx power levels and inter- site distances, respectively. For each combination of macro sites, graphs in these figures indicate decrease of AEE in case when Tx power or inter-site distance increases. This is because increase in the Tx power has higher impact on increase of site power consumption and lower influence on bit rate enlargement of the site. In addition, by increasing inter-site distance, AEE decreases due to overlapping reduction what lowers bit rates offered to the users. Considering individual BSs sites, it can be noticed from Figures 6 and 7, that site with installed two GSM (900, 1800) BSs and one UMTS 2100 BS has the lowest AEE among all sites. This is because GSM BSs has the lowest bit rate and highest power consumption, and as a result lowest AEE. On

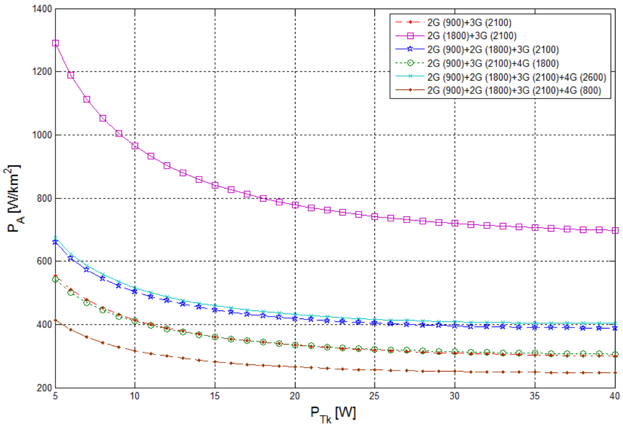

Figure 2. Interdependence of area power consumption and Tx power

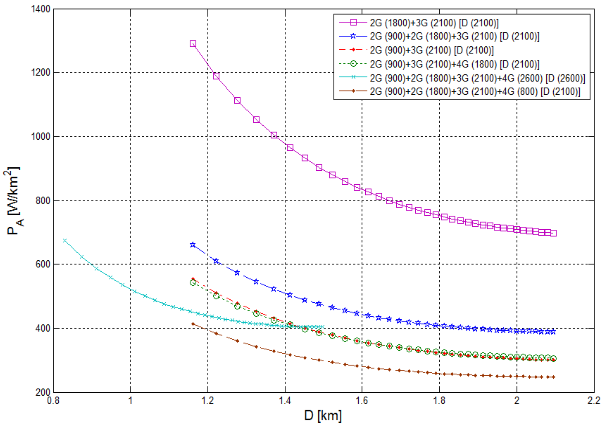

Figure 3. Interdependence of area power consumption and inter-site distance

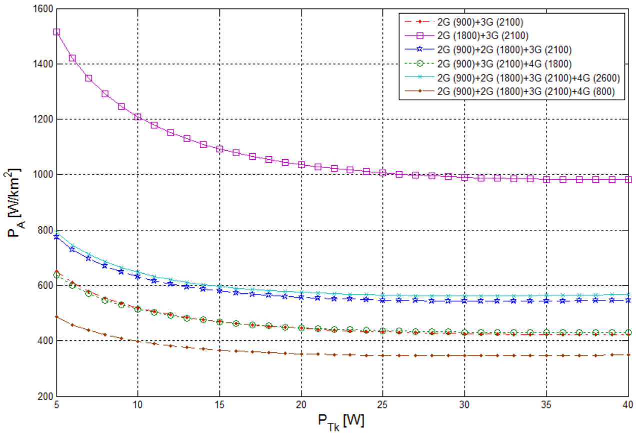

Figure 4. Interdependence of area power consumption and Tx power (for fixed inter-site distance *D*=1.4 km)

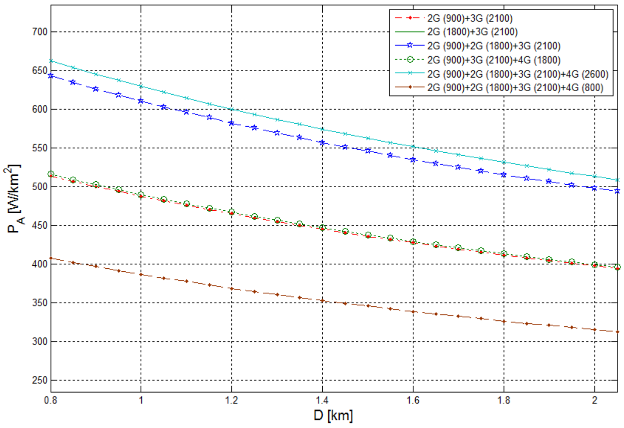

Figure 5. Interdependence of area power consumption and inter-site distance D (for fixed Tx power P_{Tk}=20 W)

the other hand, area covered by this site is the same as for the site with installed GSM 900, UMTS 2100 and LTE 1800 BSs. Generally, introducing LTE BS on site contributes significantly to increase in AEE, since LTE BS is characterised with higher bit rate and lower power consumption due to newer hardware technology.

Figure 8. shows dependence between AEE and Tx power for the same fixed inter-site distance (1.4 km) as in the case of analyses presented in Figure 4. It can be noticed that AEE decreases when Tx power increases, due to mentioned dominant influence of Tx power on site power consumption. It is worth to emphasize that graphs presented in Figure 8 have the same shape for each macro BS combination, as graphs presenting Bit per Joule energy efficiency calculated using relation (11). This is because inter-site distance in relation (11) is not parameter which can influence on Bit per Joule efficiency. On the other hand, Figure 9 shows dependence between AEE and inter-site distance, for the case of constant Tx power level (20 W). Figure confirms that introduction of newer BS technology characterised with higher bit rates and lower power consumption contributes to the improvement of site AEE.

6. CONCLUSION

In this paper, influence of the Tx power and inter-site distances on the area power consumption and area Bit per Joule efficiency of a macro BS site have been analysed. Analyses have been performed for combinations of multiple macro BSs installed on the same site. Analysed combinations differentiate in terms of number of installed BSs, corresponding BS technologies (GSM, UMTS and LTE) and its operating frequencies. According to obtained results, area power consumption mainly depends on operating frequencies of BS technologies installed on site. Sites with more BSs transmitting at higher frequencies will be less energy-efficient in terms of area power consumption and vice versa. In addition, Tx power of BSs mainly influences on Area Bit per Joule efficiency of the macro BSs site. Macro sites having BSs transmitting at higher Tx powers will have lower area Bit per Joule energy efficiency and vice versa. This is because increased Tx power contributes more to the enlargement of site power consumption in comparison with contribution to the Bit per Joule enlargement. For that reason, introducing BSs of newer technologies (e.g. LTE) on site contributes to increase of site Area Bit per Joule efficiency.

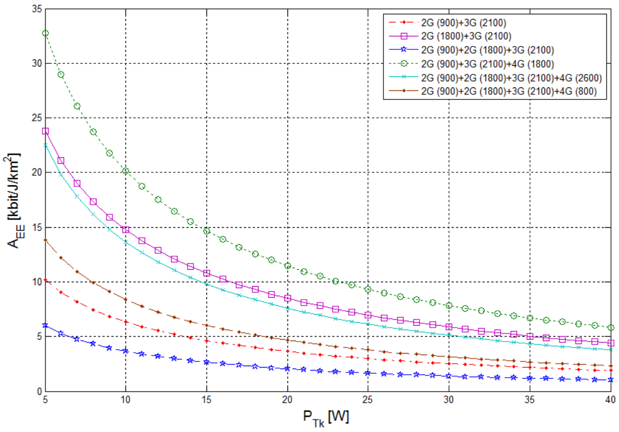

Figure 6. Interdependence of area Bit per Joule energy-efficiency and Tx power

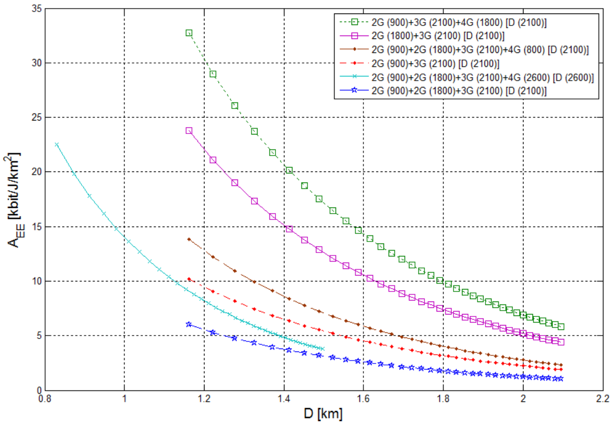

Figure 7. Interdependence of area Bit per Joule energy-efficiency and inter-site distance D (analyses for two macro BSs sites)

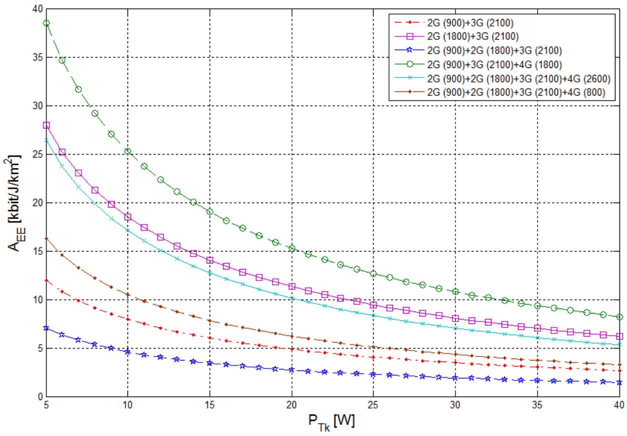

Figure 8. Interdependence of area Bit per Joule energy-efficiency and Tx power (for fixed inter-site distance D=1.4 km)

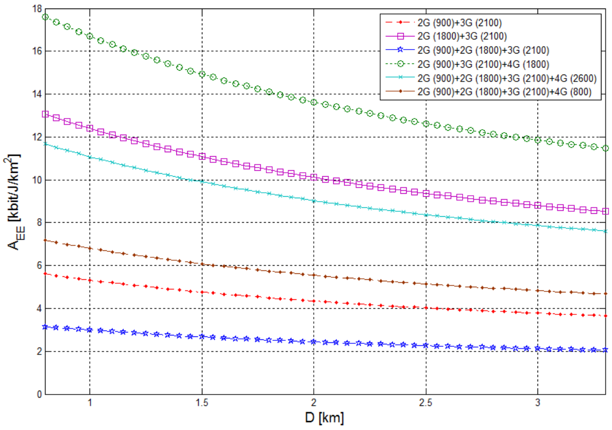

Figure 9. Interdependence of area Bit per Joule energy-efficiency and inter-site distance D (for fixed Tx power P_{Tk}=20 W

Our further research activities will be focused on investigation of area power consumption and area Bit per Joule efficiency in case of heterogeneous networks consisted of micro and different macro BSs installed on a single site.

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