Energy-efficient wireless cellular communications through network resource dynamic adaptation

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Abstract — Cellular networks represent one of the major energy consumers of communication networks and their contribution to the global carbon footprint and energy consumption continuously and rapidly increases. Improving energy efficiency of the cellular access networks become an important requirement and has recently gained considerable attention of the research community and operators. In this paper, improving cellular networks energy efficiency through dynamic adaptation of network resources is presented with foundations which justify practical realization of such approach. Paper gives insight into how the traffic pattern variations and transmitted power scaling influence on the instantaneous power consumption of the base stations. Also, impact of the base stations Tx power on two prominent energy efficiency metrics of the cellular access network is discussed. Results of a proposed optimization approach which is based on dynamic adaptation of the base stations on/off activity and the transmitted power in accordance with the spatial and temporal variations of traffic are presented. According to obtained results, dynamic adaptation of network resources can offer significant monthly energy savings on the level of complete cellular access network.

Keywords — base station, green, management, energy-efficient, wireless, cellular, power, resource

1. Introduction and related work

As part of the ICT (Information and Communications Technology) sector, mobile radio networks contribute a rather small portion of global greenhouse gas (GHG) emissions (0.2%) (Richter, 2009; Vadgama, 2009). However, energy consumed by this sector is not negligible and contributes 15–20% of the energy consumption of the entire ICT sector (Fettweis, 2008). According to estimations, the radio access part of a cellular network, more specifically the base station (BS), is a major energy consumer (Chen, 2010). The share of the BSs' energy consumption in the total cellular network energy consumption is between 55 and 80% (Ha, 2011; Guo, 2011; Wu 2012). With rising energy prices, BSs, as the most significant energy consumer in wide area cellular networks, contribute up to 50% of the total operational expenditures (OPEX) of an operator (Correia, 2010). Hence, improving the energy efficiency of cellular access networks has been an important economic issue since reducing energy consumption translates to lower operator OPEX.

A comprehensive survey of techniques dedicated to energy savings in cellular networks is provided in (Hasan, 2012). Authors explore some research issues and challenges and suggest techniques to enable an energy efficient cellular network. In particular, standardization of energy efficiency metrics, improvements in power amplifier technology, development of power saving protocols such as sleep modes, energy-aware cooperative BS power management with adaptive adjustment of BS Tx power known as "Cell zooming" are discussed. Furthermore, techniques such as: spectrum sensing, energy-aware MAC and routing, efficient resource management, cross-layer optimization and renewable energy sources are also presented.

Extensive overview of relevant challenges in the area of green cellular networks and solutions considering: relay techniques, heterogeneous cells, operator's cooperation, power and granularity control, etc., have been discussed in (Oh, 2011). In addition, using real data traces from part of the real urban area network, authors emphasize promising potential in terms of power saving that one can expect by turning off BSs during low traffic periods.

An overview of game-theoretic approaches to energy-efficient resource allocation in wireless data networks are presented in (Meshkati, 2007). Authors have introduced a number of non-cooperative and distributed power control games in which each user seeks to maximize its own utility while satisfying its QoS requirements in multiple access networks. The impact of advanced signal processing on energy efficiency and network capacity is demonstrated and the tradeoffs among throughput, delay, network capacity and energy efficiency are discussed.

In the book (Wu, Rangan, Zhang, 2012), a comprehensive discussion of academic research and relevant applications in green communications are presented. Theoretical analysis, algorithms, and practical applications for green wired and wireless communications are included. More specifically, chapter dedicated to green wireless access networks explains main challenges for implementation of "green" radio resource management in cellular networks.

Increasing the energy efficiency of the access part of cellular networks can be accomplished through a holistic approach considering improvements at components (Ferling, 2010), links (Hernon, 2010; Bogucka, 2011), and network levels (Correia, 2010; Blume, 2010). In the case of main BS equipment, (Wu, 2012) indicated several ways to achieve better energy efficiency which can be classified in energy-efficient: chip and device level designs, physical layer approaches, medium access control (MAC), cellular infrastructure, high-layer network protocols and cross-layer optimizations at the base station or network level.

However, for significant energy savings, the network level approach based on dynamic management of BS resources seems to be the most promising. Due to such expectations, our previous research activity was mainly focused on improving energy efficiency at that level of Wireless Local Area Networks (WLANs) (Lorincz, Bogarelli, 2010; Lorincz, 2011, p. 540; Lorincz, 2011, p. 648; Lorincz, 2010, p. 195). We develop optimization models based on integer linear programming and heuristic algorithms. The results obtained show that significant energy savings can be accomplished in the case of large-scale WLANs when dynamic management of the access point's activity is implemented. In this paper, we also present an overview of our further research activities on the network level of the wide area cellular access networks. They are dedicated to defining models that express the interdependence between BS transmit (Tx) power or traffic variations on instantaneous BS power consumption (Lorincz, 2012, p. 4310; Lorincz, Dimitrov, 2012). Furthermore, the analysis of the influence of introducing BSs of newer technologies (e.g. Long Term Evolution – LTE) on network energy metrics is performed in Lorincz (2012, p. 161). In addition, our latest research is focused on the analysis of possible energy savings in the case of performing dynamic management for BSs activity and Tx powers (Lorincz, 2012, p. 24).

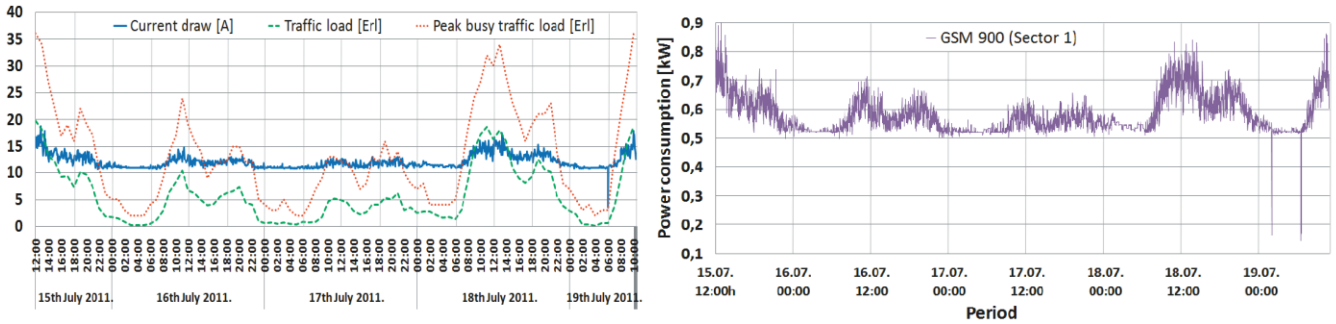
The rest of the paper is organized as follows: based on the measurement results obtained for real BS sites (BSSs), the impact of daily traffic variations on the BS power consumption is presented in Section 2 and the influence of BSs' Tx power on their instantaneous power consumption is discussed in Section 3. The impact of BSs' Tx power on network energy efficiency expressed by the most prominent energy metrics is presented in Section 4. Section 5 explains how dynamic management of network resources can improve network energy efficiency through describing the proposed optimization approach, the network model used for simulation, and the numerical results obtained as a result of simulation. Finally, some concluding remarks are given in Section 6.

2. Impact of traffic variations on BS power consumption

In order to indicate how traffic variations influence instantaneous BS power consumption, we have performed extensive on-site measurements at a fully operated BSS (Lorincz, 2012, p. 4310; Lorincz & Dimitrov, 2011). The site at which measurements were performed is located in an urban-dense area of a medium sized city and is one of the most loaded city sites in terms of voice and data traffic flows. BSs of

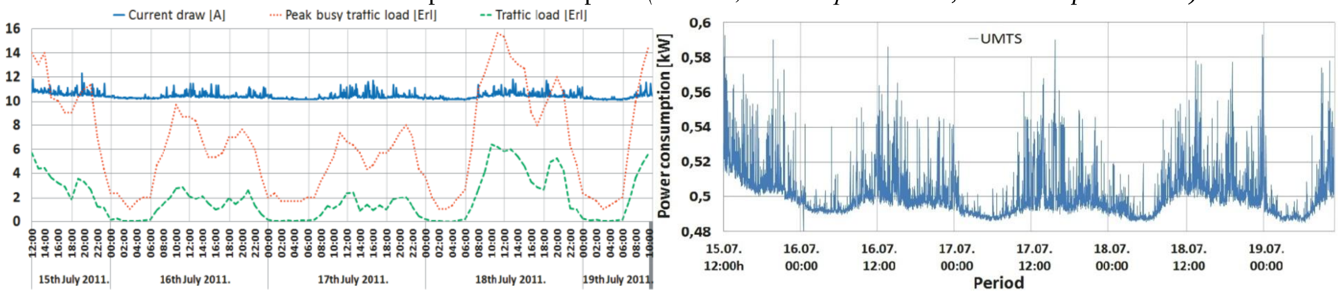
Table 1. Characteristics of UMTS and GSM BSs installed on the analyzed site.

Characteristics of on-site BSs	UMTS	GSM 900 BS1	GSM 900 BS2
Production year	2010	2003	2000
Frequency band	2,100 MHz	900 MHz	900 MHz
Number of BS racks	1	1	1
Number of sectors covered by one BS rack	3	1	2
Number of transceivers in one base station rack	3	7	8
Number of TRXs per sector	1/1/1 (data)	7 (voice)	3/1 (voice) 1/1 (data)
Output power per sector	25 W	50 W	50 W
Number of combiners in rack	integrated in RF module	3	3
Number of antennas per sector	1	2	4
Number of antenna cables per antenna	2	2	2
Coverage angle of BS antennas	360°	120°	240°
Antenna cable diameter	7/8”		



a) b)

Figure 1. (Lorincz, 2012, p: 4310) For GSM BS (Sector 1) a) comparison between electric current draw and traffic load, b) variations in instantaneous power consumption *(© 2012, MDPI open access, used with permission)*



a) b)

Figure 2. (Lorincz, 2012, p: 4310) For UMTS BS a) comparison between electric current draw and traffic load, b) variations in instantaneous power consumption *(© 2012, MDPI open access, used with permission)*

the two different cellular access technologies, more specifically the Global System for Mobile Communications (GSM 900) and the Universal Mobile Telecommunications System (UMTS 2100) were analyzed. Network operators configure the cellular network in such way that the first analyzed GSM BS (BS1) is primarily dedicated to accepting voice traffic while the second BS type (UMTS) predominantly serves data users. BS racks are a type of indoor cabinet located inside a protected room dedicated solely to keeping site equipment. An overview of the analyzed BSs characteristics is shown in Table 1.

We performed continuous five-day measurements in the period from 15 July starting at 12:00 until 19 July ending at 10:00. It is worth emphasizing that the measuring period starts on Friday and finishes on Tuesday, which enables identification of possible differences in the BSs' power consumption between working and weekend days. Variations in the instantaneous power consumption of the GSM 900 BS1 (Sector 1) and UMTS 2100 BSs are presented in Figures 1b and 2b, respectively. Since BSs are battery powered with a constant voltage of 53.6 V, the presented power consumptions of the individual BSs were obtained through multiplying this voltage by the measured instantaneous BS electric current presented in Figures 1a and 2a.

According to Figures 1 and 2, the instantaneous power consumption varies during a day and these variations are inherent for all the mobile technologies analyzed (GSM 900 and UMTS 2100). Moreover, a direct correlation between the electric current draw and variations in the traffic load could be observed.

Information about average and peak (maximal) traffic load for all three sectors on an hourly basis was obtained from the specialized monitoring system of an operator. Although the level of correlation in the graphs in Figures 1a and 2a might seem negligible, it is a consequence of the presentation approach, which uses the same axes to present different measuring parameters (erlangs and amperes). On the other hand, Figures 1b and 1b indicate that the correlation between measured current and traffic load is reflected in the power consumption changes.

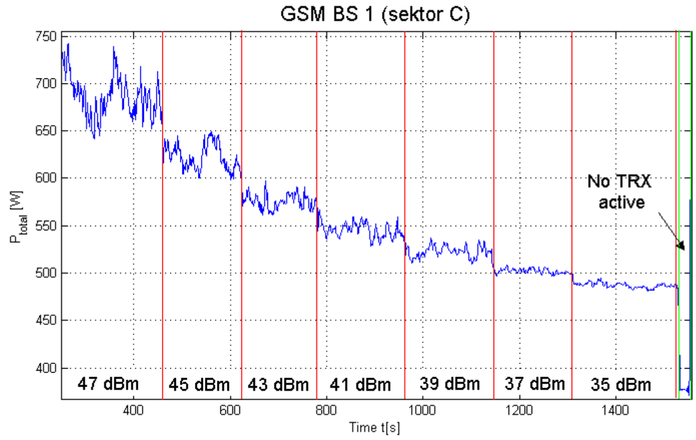
The shape of the power consumption pattern presented in Figures 1b and 2b does not depend on the transmission technology and is basically identical for each analyzed BS. This means that the lowest consumption was observed between 02:00 and 06:00 while the highest power consumption was recorded between 10:00 and 14:00 (peak hours) for each of the analyzed days. Also, during peak hours, for each BS differences of the power consumptions between weekend (16 and 17 July) and working (15, 18, and 19 July) days can be clearly noticed for each BS.

Hence, changes in the presented power consumption are directly influenced by daily traffic pattern variations. It can be said that a decrease in user activity during a day results in a decrease in the instantaneous power consumption of a BS and vice versa. The reason is that the additional hardware and processing resources must be activated by a BS in order to accommodate the increased traffic load. Therefore, the repeated night/day changes in the activity of users have impacted on the instantaneous power consumption of BSs.

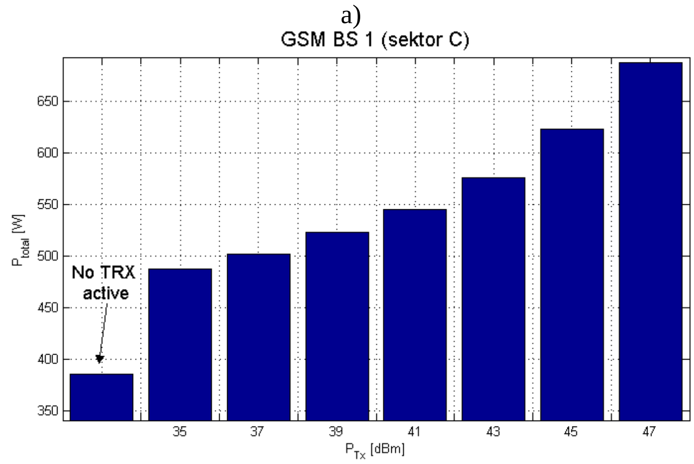
Although in our analyses a UMTS BS rack covers three sectors (360º) around a BS site, a GSM BS rack covers one sector (120º), and the absolute values of the instantaneous power consumption in the case of the GSM BS are higher than those of the UMTS BS (Figures 1b and 2b). This is the consequence of two important reasons. The first reason is that the number of transceivers (TRXs) used in the GSM BS configuration, according to Table 1, is equal to seven. On the other hand, the UMTS BS is configured to contain three TRXs (one per sector). The number of TRXs has the important influence on the total BS power consumption, since each TRX has its own power amplifier, which, as an individual component, has the highest share in the total BS consumption. The second reason is the different ages of the BSs: the GSM BS is eight years old while the UMTS BS is only one year old. Generally, newer BSs have newer hardware which is less prone to traffic variations and more energy efficient. Newer hardware also may imply better power amplifier efficiency, which additionally contributes to reductions in the BS power consumptions.

3. Influence of transmit power on BS power consumption

In order to show how the Tx power of the BS influences instantaneous BS power consumption, we perform on-site measurements for the case of a fully operated indoor GSM 900 BS. It is worth noting that the measurements described in this and previous sections for GSM BSs for which measurements differ. Measurement results described in this section were obtained from the GSM BS of another operator manufactured by a different vendor and located on a different BSSs. However, the location of the BSS is again in the centre of a medium size city that is densely populated with mobile users. The parameters of the analyzed BS indicated as GSM 900 BS2 are presented in Table 1. The GSM 900 BS2 covers two



a)



b)

Figure 3. Influence of Tx power on GSM BS energy consumption obtained through: a) real on site measurement, b) approximation based on measurement results

sectors (C/B) around the BSS and is configured with a different number of active TRXs for offering voice/data services in each sector.

Since we want to show how changes in the Tx power influence the power consumption of BSs covering a single sector, in the measurement phase we turn off the part of the BS2 used for covering sector B. This means that we shut down one voice and data TRX (Table 1) used for transferring sector B traffic. After that, only the parts of the BS2 dedicated to covering sector C remain active (three TRXs for voice and one for data traffic). It is worth emphasizing that the modification of the BS2 configuration in terms of changing Tx power and shutting down TRXs was performed during peak hours. Since we have shown in the previous section that instantaneous power consumption is highest during peak hours, with this approach we want to take into account not only the influence of the Tx power on BS power consumption but also the influence of user traffics. On the other hand, such modifications on the BS configuration are followed by the migration of users served by the analyzed BS to other neighboring BSs.

We perform the measurements for BS2 instantaneous power consumptions during the decrease of the BS Tx power. Approximately every two minutes, we reduce the BS2 Tx power from maximal values (47 dBm) in the steps of 2 dBm until it reaches the lowest possible Tx power for detecting the BS signals (35 dBm). The changes of the BS Tx power were performed manually using software, based on remote access from the operation and management room of an operator.

The measurement results are presented in Figure 3a. According to the obtained results, we can see that the level of the BS Tx power has some impact on the BS instantaneous power consumption. With the decrease of the Tx power, the instantaneous BS Tx power also decreases and vice versa. As in the case of measurements presented in the previous section, the changes in the BS power consumption presented in Figure 3a are obtained by multiplying the measured current draw by the constant DC voltage (24 V)

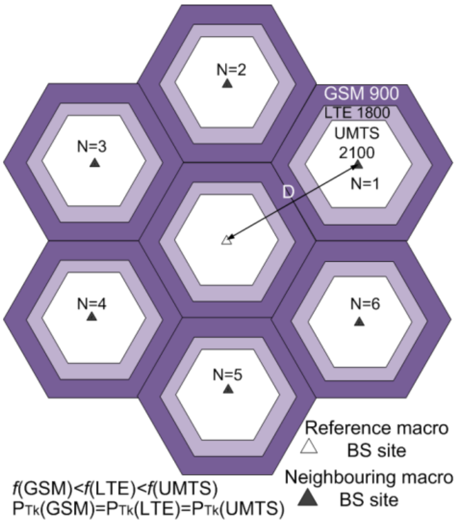


Figure 4. Heterogeneous network environment consisting of different macro BSs installed on BS sites

Table 2. Analyzed scenarios in terms of macro BSs' Tx power and ISDs

Scenario	Macro ISD	Tx power of macro reference BS	Tx power of macro neighboring BS
Scenario 1	Fixed (1.4 km)	Variable (5–40 W)	Variable (5–40 W)
Scenario 2	Fixed (1.4 km)	Fixed (20 W)	Variable (5–40 W)

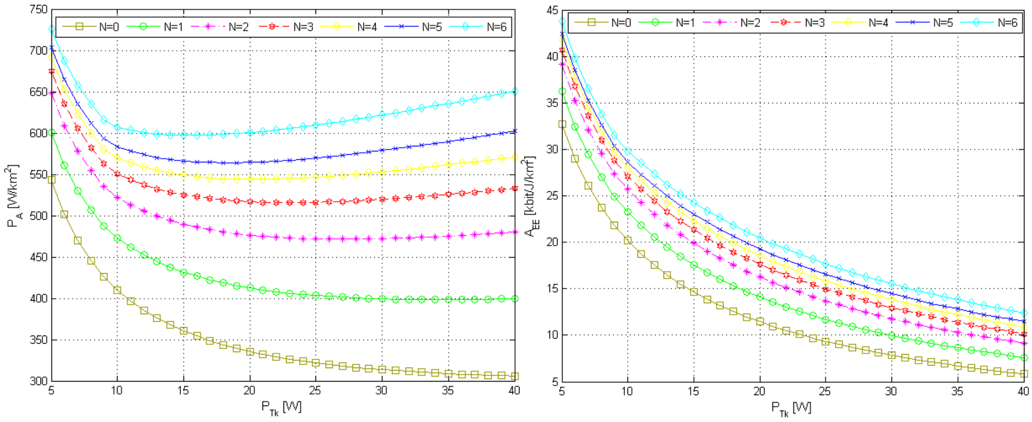
generated by the BS battery supply. The fluctuations of the BS instantaneous power consumption presented in Figure 3a for a fixed BS Tx power level are one of consequences of user activities and the migration of users among BSs. According to Figure 3b, we obtain a total of eight averaged measurement results: seven for each Tx power level and an additional one for the case when all TRXs are completely turned off. It can be noticed that the linear approximation can be used in the case of describing the interdependence between the BS Tx power and the BS instantaneous power consumption. Also, shutting down all TRXs of the BS still results in remaining some power consumption. The remaining power consumption is not negligible, and for the configuration of the analyzed BS, the remaining power consumption is equal to 48.1% of the total maximal BS power consumption.

4. Impact of transmit power on network energy efficiency

According to the results presented in the previous section, scaling macro BS Tx power can result in different power consumptions of BSs. Therefore, we perform analyses to figure out how the scale of the Tx power influences the energy-efficiency metric of a cellular network (Lorincz, 2012, p. 161). In the analyses, we take into account the heterogeneous nature of already deployed cellular networks. Such networks consist of macro BSs of different technologies (GSM, UMTS, LTE) installed on the same macro BSS. The addition of the new BS technology on existing BSSs is motivated by legislative regulations, easier installation of the new technology, and financial savings.

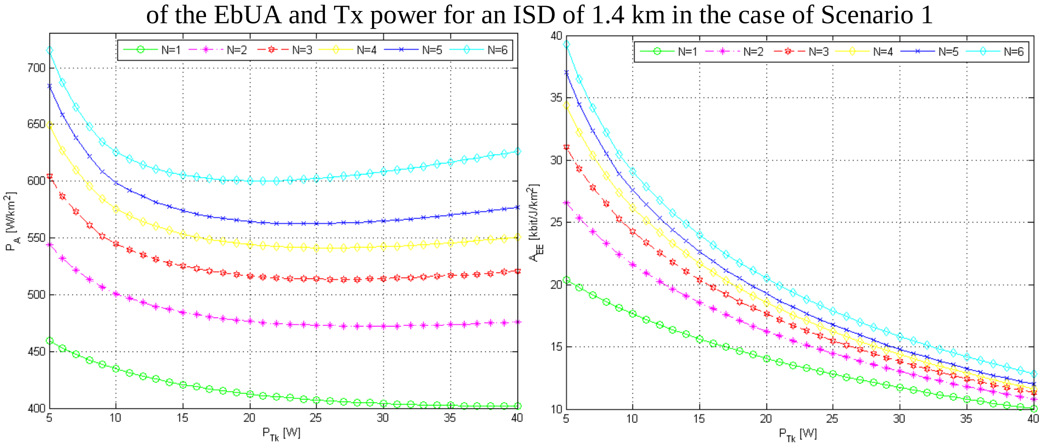
As the most prominent metrics of the energy efficiency in cellular networks, we use the Power per Unit Area (PUA) metric measured in watts per square kilometer and the Energy per bit and Unit Area (EbUA) metric measured in bits per joule per square kilometer (Imran, 2012). With the aids of such metrics, dissimilar perspectives on the energy consumption of a radio access network (RAN) can be obtained. The PUA metric (P_A) focuses on the total power consumption used to ensure the coverage of a certain area, while the EbUA metric (A_{EE}) provides the information about the bit delivery energy efficiency for a covered area. Based on these two metrics, it is possible to indicate the influence of the Tx powers on the energy efficiency of current cellular networks which are heterogeneous in terms of installed access technologies.

In the analyses, we regard a macro BSS as an indoor site placed at the center of a hexagonal cell (Figure 4). The reference site contains macro BSs of three different technologies denoted as GSM 900, UMTS 2100, and LTE 1800 BSs, where the numbers indicate the operating frequencies of BSs in megahertz. The *neighboring* BSSs surround a *reference* BSS and they are equal in terms of the number of installed macro BSs, corresponding technologies, and operating frequencies. It is assumed that each macro BS ensures omnidirectional convergence around the macro BSS characterized by a radiation pattern of 120º per



a) b)

Figure 5). (a) Interdependence of the PUA and Tx power for an ISD of 1.4 km in the case of Scenario 1; (b) interdependence of the EbUA and Tx power for an ISD of 1.4 km in the case of Scenario 1



a) b)

Figure 6. (a) Interdependence of the PUA and Tx power of neighboring BSSs in the case of Scenario 2; (b) interdependence of the EbUA efficiency and Tx power in the case of Scenario 2

sector. To reduce the complexity, we assume that each neighboring BSS is located at an equal distance *D* from the reference BSS. Also, for simplicity, we assume that, regardless of the applied BS technology, all BSs installed on the site always transmit at equal Tx power levels.

A layered approach in terms of areas covered by radio signals around BS sites is assumed in the analyses. This means that one independent layer of signal coverage represents the coverage area of one BS technology (Figure 4). Three overlapping layers of coverage areas specific to the corresponding BS technology exist around each BSS. The reason is that three different types of macro BS technologies are assumed to be installed on a single macro BSS.

We have analyzed the influence of different numbers of neighboring macro BSSs and corresponding Tx powers on the network energy efficiency. The analysis is done for two different scenarios presented in Table 2. In Scenario 1, the Tx power of neighboring and reference BSSs changes concurrently from 5 to 40 W in steps of 1 W. The inter-site distance (ISD) *D* is fixed at 1.4 km, which is a typical ISD for macro BSSs located in urban areas. In Scenario 2, for the same fixed ISD, the Tx power of the reference site has a constant value of 20 W while the Tx power of all neighboring sites varies in steps of 1 W from 5 to 40 W.

The influence of the BS Tx power on the PUA and EbUA for Scenarios 1 and 2 is presented in Figures 5 and 6, respectively. By placing every new neighboring macro BSS in the simulation, different graph lines were obtained on the figures. Generally, in both scenarios the PUA and EbUA increase with the allocation of every new BSS. This is due to the fact that every new BSS leads to an increase in the power consumption and the achievable bit rate. However, since metrics the PUA and EbUA have opposite demands, network operators tend towards lower PUA and higher EbUA, which means that the best possible trade-off among these two metrics must be achieved.

A change in the trend caused by the increase of the Tx power has a parabolic shape of the PUA changes as indicated in Figures 5a and 6a. Up to a certain Tx power, the PUA decreases because of the increase in the area covered by the BSSs. After that point, the BSS power consumption becomes more dominant in comparison with the area covered and the PUA starts to increase. On the other hand, Figures 5b and 6b indicate the hyperbolic shape of the EbUA changes. Although unexpected, a decrease in the Tx power of macro BSSs will result in an increase of the EbUA and vice versa. The reason is that the transmission at higher Tx power results in a larger overall coverage area, and in order to ensure the service in this larger area, a higher average energy is needed for transmission of 1 kilobits per second. According to the results obtained through simulation of these practical scenarios, mobile operators may find a range of 15 W to 20 W to be optimal with regard to the network energy efficiency.

5. Dynamic management of network resources

5.1. Approaches for improving energy efficiency

From the results presented in the previous sections, three facts can be noticed:

1. Although the power consumption of BSs varies during a day in accordance with variations in the traffic pattern, the BS consumption is still significant during off-peak periods characterized by almost negligible traffic intensity (Figures 1 and 2).
2. Changing the Tx power of a BS during a day would result in changes in the BS power consumption (Figure 3). In this case, the total daily power consumption of the BS would be lower compared with the daily consumption inherent in the current BS configurations characterized by continuous transmission most often at the highest Tx power.
3. Dynamic management of BSs' Tx power would influence the energy-efficiency metrics of the complete cellular network containing the overlapping layers of heterogeneous cells. Additionally, there exists a range of optimized BS Tx power allocations which are more favorable in terms of the network energy efficiency (Figures 5 and 6) for specific BSs allocations.

Based on the mentioned facts, two approaches are proposed in order to save the energy at the level of the whole network (Lorincz, 2012, p. 24). The approaches are based on the dynamic adaptation of network resources controlled from a centralized location of the network operator. The first approach is based on switching off unused or underused BSs without compromising coverage and service quality in periods of lower user activity. Hence, the proposed approach considers slow temporal variations of traffic through dynamic switching on and off of complete BSSs according to the daily traffic variations. To consider highly dynamic spatial traffic fluctuations, the second approach is dedicated to adaptively scaling BS Tx power according to the capacity demands. For the higher or lower Tx power levels, the proposed method would help adaptively increase or decrease the capacity and the coverage of the BSs, respectively. Analyses are performed using four discrete macro BS Tx power levels equal to 10 W, 20 W, 30 W, and 40 W. According to the space and time fluctuations of users, the proposed approach is based on dynamic selections of Tx powers among the mentioned levels for BSSs that remain active.

In (Lorincz 2012, p. 24), we proposed an optimization model in order to estimate the effectiveness of such an energy-efficient network management approach. With the proposed optimization model, it is possible to analyze the most important element of dynamic radio resource management; that is, the influence on network energy savings of BS daily switching granularity and selection of the level of Tx power for each BS that remains active when switching takes place.

5.2. Network model

The proposed model has been tested on a set of real size UMTS network instances that are similar to those of real UMTS networks. In order to generate the network instances, we have developed an instance generator (IG) as a software solution programmed in the C++ programming language. Based on a predefined set of input parameters, the IG generates analyzed UMTS network instances. We perform analyses on 12 different network instances and Figures 7a and 7b show the structure of the two arbitrarily

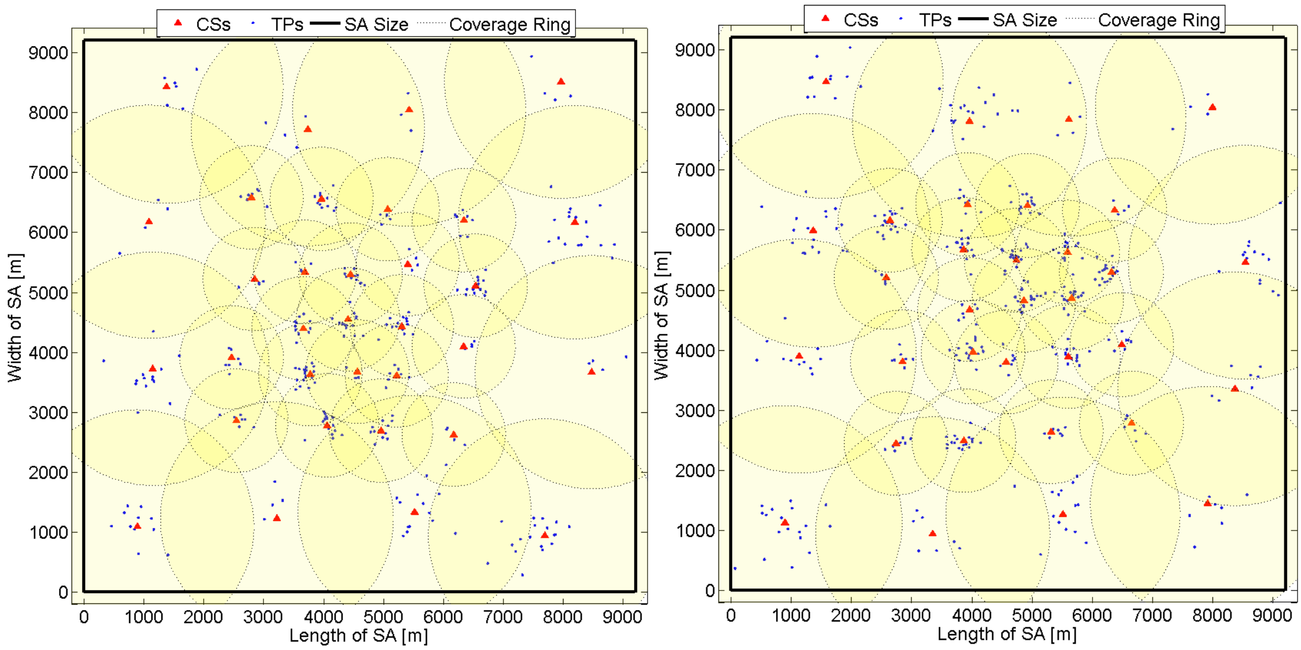


Figure 7. Allocation of CSs (BSSs) and TPs (UTs) inside a SA for: a) one-sector BSSs (Instance 4), b) three-sector BSSs (Instance 11)

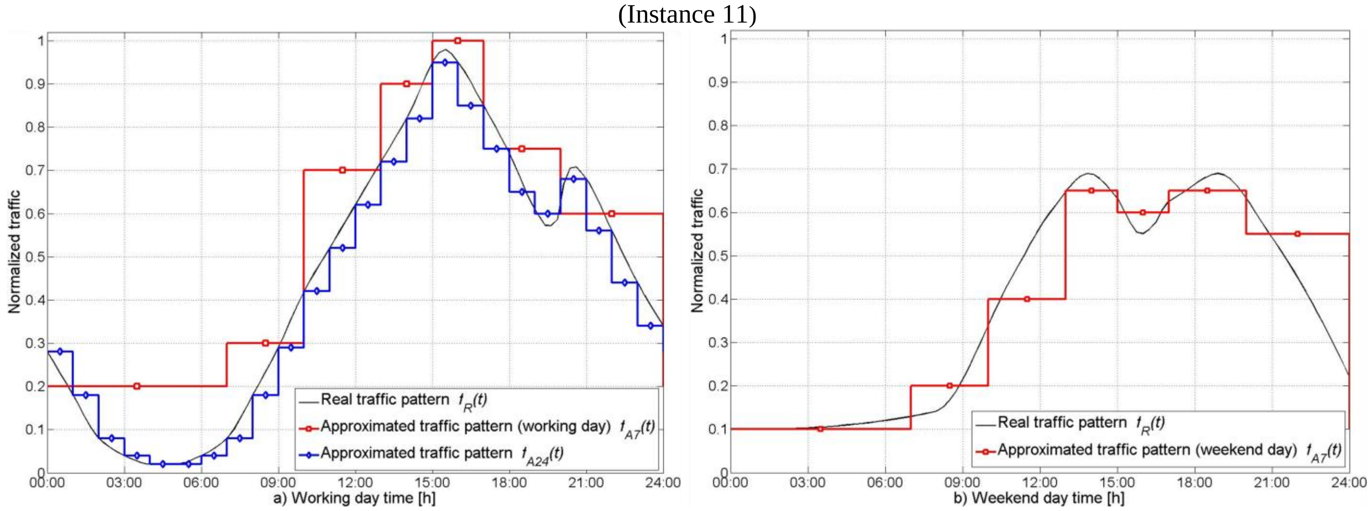


Figure 8. (Lorincz, 2012, p. 24) Approximation of the real traffic pattern for: a) a working day using seven (f_{A7}) and 24 (f_{A24}) time periods, b) a weekend day using seven (f_{A7}) time periods *(© 2012, SpringerOpen, used with permission)*

selected UMTS network instances (Instances 4 and 11). In the analyses, two different types of network instances were assumed. In the first, all of the BSSs have omnidirectional antennas; they are also called one-sector (cell) BSSs. Those instances are marked as Instances 1–6. The second network type is represented by instances indicated as Instances 7–12 which contain only the three-sector BSSs. Due to expected differences in potential energy-savings, we decided to investigate these two different network types separately. The same configuration of macro BSs is assumed in terms of the number of transceivers, power amplifiers, combiners, and antennas used for covering a single sector.

In the case of every analyzed network instance, we performed a random allocation of 33 macro UMTS BSSs inside a service area (SA) of 85 km^2 (Figures 7a and 7b). On the figures, we show those BSSs as coverage sites (CSs), since those BSSs ensure complete coverage of the SA. It is reasonable to believe that, from a practical point of view, the use of 33 BSSs inside an SA of that size corresponds fairly well to the number of BSSs that would be allocated by a single operator in the real coverage planning case. Hence, the analyzed SA corresponds to a broader region of a medium sized city. In order to increase the similarity of every analyzed instance to a real cellular network of an operator in a medium size city, we assume three different propagation areas, classified as urban-dense, urban, and suburban (rural) areas.

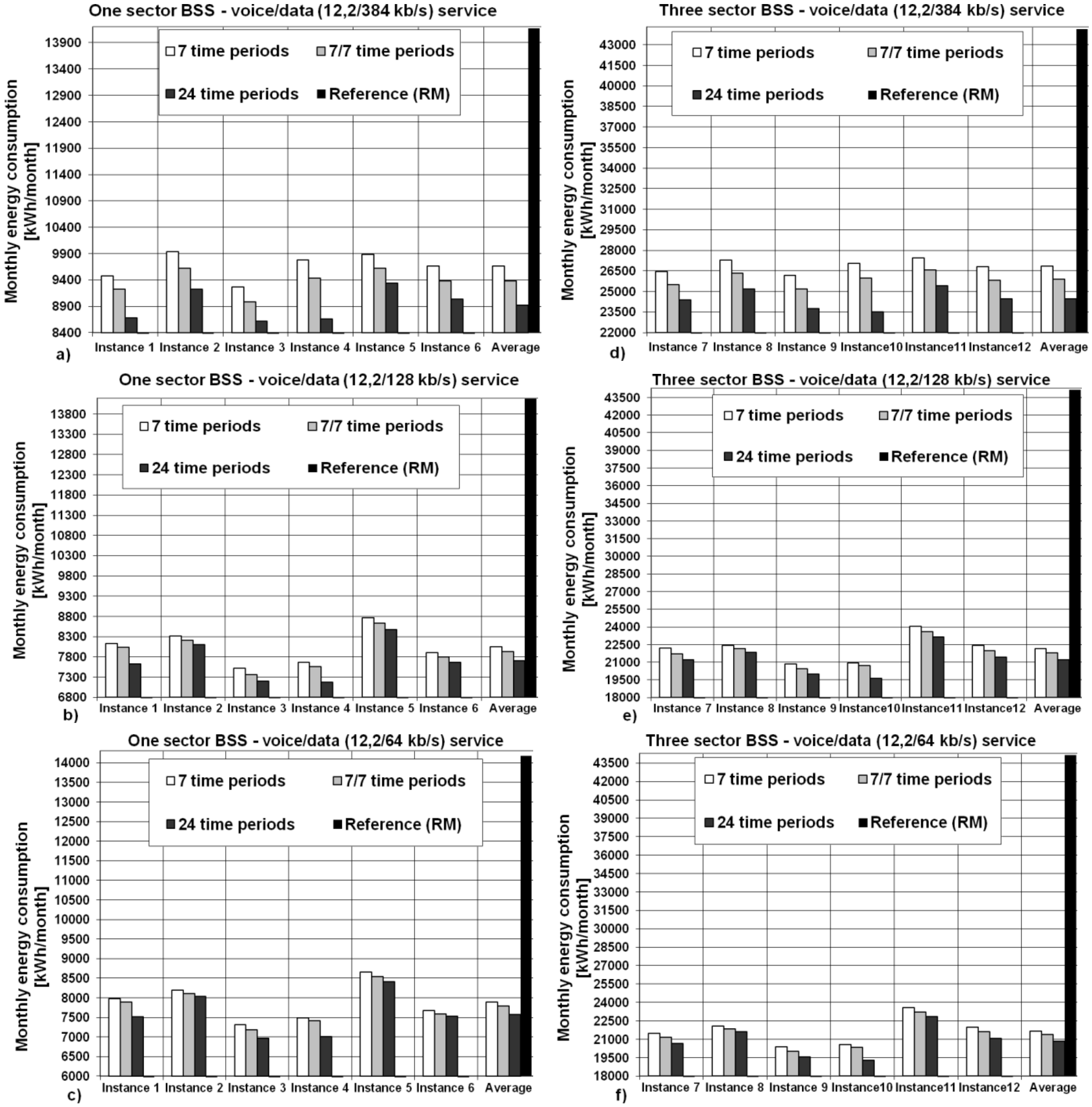


Figure 9. Statistics for monthly energy consumption for each of the analyzed instances with one- and three-sector BSSs guaranteeing a voice/data service equal to: a and d) 12.2/384 kb/s; b and e) 12.2/128 kb/s; f and c) 12.2/64 kb/s

According to these morphology categories, Figures 7a and 7b indicate a decrease in BSS density from the center to a border region of the SA.

Furthermore, a different number of user terminals (UTs) representing different types of demands in network services are allocated inside the SA of each network instance (Figures 7a and 7b). In order to differentiate users demands in voice and data services, each UT is grouped into traffic clusters (TCs). The TC is a group consisting of one or more UTs demanding a specific type of service and they are allocated at close proximity to each other (Figure 7). We use two types of TCs denoted as voice and data TCs. For simplicity, we assume that users in a voice cluster always demand voice service while users in a data cluster request only data service.

TCs are allocated randomly inside the coverage areas of BSSs as presented in Figures 7a and 7b. The number of allocated TCs inside the coverage area of each BSS (CS) is adapted to the capacity of the network and corresponding BSSs. Thus, instances containing three-sector BSSs (Instance 11 in Figure 7b) have a higher number of allocated TCs in comparison with the instances containing a one-sector BSS (Instance 4 in Figure 7a). Moreover, the allocation densities of TCs are higher around locations closer to the BSSs. This is due to the common approach in radio network planning where operators strive to allocate BSSs in the center of traffic hot spots.

Since we want to show how the BS switching granularity influences network energy consumptions, we perform an approximation of the real traffic pattern presented in Section 2. In Figures 8a and 8b, three distinct approximation types were used for discretization of the real traffic pattern $f_R(t)$. The first type assumes equal traffic patterns for working and weekend days and the discretization function $f_{A7}(t)$ is based on seven discrete time periods during one day (Figure 8a). The second approximation is also based on seven discrete time periods, but this approximation takes into account differences among traffic profiles of the working and weekend days (Figures 8a and 8b). The last approximation type assumes a finer-grained discretization with 24 time periods (f_{A24}) in the case of a working day only (Figure 8a). Besides the impact of switching granularity, with such a traffic approximation we can also observe the influence of different working and weekend-day traffic profiles on network power consumptions.

5.3. Numerical results

A reference model (RM) has been introduced for evaluating the quality of the obtained optimization results. The RM is a network model with working properties typical for today's cellular UMTS networks. This means that we assume that the RM UMTS network consists of 33 BSs continuously transmitting at a maximal Tx power equal to 40 W. Additionally, dynamic on/off management of the BSs' activity and adaptations of the Tx power cannot be performed in the case of the RM. Consequently, each BSS in the RM has the constant power consumption during a day. Thus, the monthly values of energy consumption of RMs for single-sector and three-sector network instances would be different, as indicated by the black vertical bars in Figure 9. The higher monthly energy consumption of the RM for three-sector network instances is due to the higher power consumption of BSs' racks covering three sectors.

Optimization results in terms of monthly energy consumptions for different voice/data service rates guaranteed to the users are presented in Figures 9a–c for one-sector and in Figures 9d–f for three-sector instances. In comparison with the monthly energy consumptions of the RM, the dynamic management of network resources offers significant reductions in the monthly energy consumptions for each of the analyzed instances. For the same type of traffic approximation, we can notice differences in monthly energy consumption among network instances guaranteeing the same voice/data service rates. This is due to differences among analyzed network instances which contain different allocations of TCs and CSs. Also, higher absolute values of monthly energy consumptions have been recorded for network instances having three-sector BSSs due to the higher instantaneous power consumptions of such BSs.

In addition to this, Figure 9 indicates a significant influence of guaranteed service rates on instantaneous network power consumptions. If we consider a specific network instance with a corresponding type of traffic approximation, Figures 9a–f indicate that guaranteeing higher voice/data service rates causes larger monthly energy consumption of the network. This is due to the need to activate a higher volume of network resources during one month to accommodate more demanding service rates. Therefore, ensuring higher service rates imposes higher network energy consumption, even when energy-efficient resource management is used.

Additionally, in Figure 9 it can be seen that switching granularity influences the monthly energy consumption. It can be said that higher switching granularity leads to lower monthly energy consumptions of the network. The reason is that the finer-grained temporal control of network resources enables better adaptation to time and space traffic pattern variations. For example, the vertical bars in Figure 9 for 7/7 time periods indicate monthly energy consumptions taking into account the different traffic patterns at the weekend and on working days. Compared with traffic approximation which neglects weekend days (seven time periods approximation), lower monthly energy consumptions for the same instances can be perceived when traffic patterns of weekend days are considered (7/7 time periods). Even larger differences can be observed among monthly energy consumption values obtained for traffic approximations with lower (seven time periods) and higher (24 time periods) values of switching granularity. This further confirms that higher energy savings can be obtained if finer-grained temporal control is used.

As an example, we can analyze the values of average monthly energy consumptions obtained for all three-sector instances in the case of ensuring 12.2/384 kilobits per second (kb/s) voice/data service rates (the rightmost bars in Figure 9d). The difference in monthly energy consumption between the RM and the 24 time period approximation on a yearly level is equal to 235,960.03 kilowatts per hour (kWh). Translated into financial savings, this leads to a 377,536.04 € annual reduction at the network level. If we take into account energy savings for a network of this size, we can observe that switching granularity would play an important role in the development of energy-efficient network management algorithms. Hence, the switching frequencies of BSs must be closely related with the intensity of traffic changes if the goal is to achieve the highest monthly energy savings on the network level.

6. Conclusion

In this paper, concept for energy-efficient wireless cellular communications based on dynamic network resource adaptation is presented. In addition, explanations of foundations which justify practical realization of the proposed concept are given. More specifically, through real on site measurements is shown that BSs consume significant portion of the energy even when traffic activity is low. Shutting down some BSs during such periods is reasonable approach for improving energy-efficiency. Also, scaling BS Tx power according to the coverage and capacity demands results with changes in the instantaneous BS power consumption. Such approach offers lower daily/monthly energy consumption of the BSs in comparison with current approach based on continues transmission at the highest Tx power. In addition, for specific allocation of the BSS there is an optimal range of the BS Tx powers which are more favorable in terms of the network energy efficiency. In comparison with the operating concept characteristic for today’s cellular networks, it is shown that the proposed optimization concept tested on the set of the real size network instances can offer significant monthly energy savings. Our future research activity will be focused on development of algorithms which will enable energy efficient management of network resources.

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