Energy-Efficient Cellular Network Design Based On User's Mobility and Service Characteristics

Haibao Ren†,Ming Zhao†,Wuyang Zhou†,Jinkang Zhu†, and Peng Dong‡
† Wireless Information Network Lab.
Department of Electronic Engineering and Information Science
University of Science and Technology of China,Hefei,Anhui,China 230027
Email:rhaibao@mail.ustc.edu.cn,{zhaoming,wyzhou,jkzhu}@ustc.edu.cn
‡ Research Institute of China Mobile, Beijing, P. R. China, 10053
Email:dongpeng@chinamobile.com

***Abstract*—In cellular networks, base station must reserve some resource for the possible handoff which affects the energy efficiency of the system. In this paper, we establish a theoretical model to maximizing the energy efficiency (EE) from the aspects of users' mobility and service duration. After analyzing the probability of handoff in service with user mobility and service characteristics, we introduce a dynamic energy efficiency (DEE) function. With the DEE function, an optimization problem under the constraint of maximal power is formulated to determine the optimal cell radius to maximize the DEE. We prove the existence of the unique optimal cell radius and propose an algorithm to solve the problem. Numerical results show the relationship between the optimal cell radius and different users' mobility and service characteristics, and indicate that the optimal radius is increasing both in the users' average velocity and in the average service duration. This work can provide a reliable theoretical basis for green design of cellular networks.**

I. Introduction

Over the past years, mobile communication has shown exponentially increasing energy consuming figures, doubling almost every 4 years, which arouses significant attention both in industry and academia. Moreover, the radio access network, more specifically the base stations consumes almost 80% of the power in mobile telecommunications. So energy-efficient radio access network design is very important[1][2].

There are some levers to lower the energy consumption of wireless access networks. An important approach is to improve the deployment strategies satisfying user's requirement such as coverage and spectral efficiency. Some of the base stations can be switched off in low traffic period to improve energy efficiency[3][4]. Total network base station energy cost vs. deployment is discussed in [5]. Heterogeneous cellular mobile radio networks is proved to be area energy efficient while the target rate requirement is high due to the introduction of micro cells which consuming much less power into the existing cellular networks[2][6].

All of the prior works didn't consider the mobile user's mobility which is the most important characteristic of mobile networks. Handoff would happen when the user in service moves from one cell to the other, so the resource should be reserved to avoid the blocking probability. Handoff with service on is called service handoff in this paper. Considering the service handoff, traditional energy efficiency function should be rewritten to capture the user's mobility and service characteristics.

In this paper, we investigate the relationship between service handoff and the network energy efficiency function. First, we deduce the probability of service handoff under some basic assumptions, and a dynamic energy efficiency function is given by modifying the static function we have defined. Then we formulate the problem that is maximization the DEE while satisfying some constraints and an important theorem that the existing of an optimal cell radius is proved by convex optimization theory. We propose an adjusting strategy of cell coverage for energy-efficient network design. Simulation results show our analysis is accurate enough and it can be used easily for the operator of network.

II. Service Handoff Analysis And Dynamic Energy Efficiency Function

To reduce the blocking probability in cellular networks, resource reservation is needed for users in service during handoff. However, the reservation will decrease the area spectral efficiency. So we propose the dynamic energy efficiency(DEE) function in this section to describe the effective energy efficiency of cellular networks while considering service handoff.

A. Probability of Service Handoff

The probability of service handoff when users move out the cell's coverage is analysis in this subsection. In this paper the coverage of a single cell is modeled as a simple circle with radius R as depicted in Fig.1. The points A and B are the service origination point and termination point respectively. Due to user's mobility, service handoff may happen during service duration. In our analysis, we make the following assumptions[7]:

- The angle Θ of moving direction is uniformly distributed between 0 and 2π and keep constant during service duration.
- The service origination point is uniformly distributed in the cell's coverage, thus the density function is $f_{X,A}(x,y) = \frac{1}{\pi R^2}$, and its polar coordinate form is $f_{X,A}(r,\alpha) = \frac{r}{\pi R^2}$, where $r \in [0,R], \alpha \in [0,2\pi]$.

- The service duration T is exponentially distributed with density function $f_T(t) = \mu e^{-\mu t}$, so the joint density function of independent random variables Θ and T is: $f_{\Theta,T}(\theta,t) = \frac{\mu e^{-\mu t}}{2\pi}$ for $0 \leq \theta \leq 2\pi$ and $t > 0$.

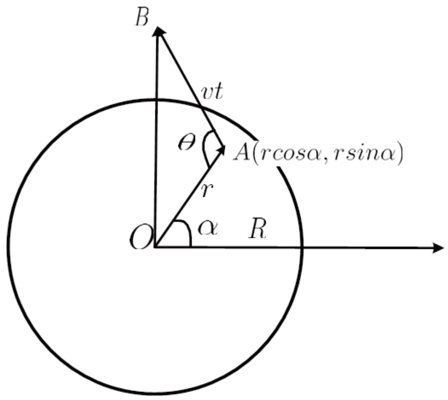

Fig. 1. Sketch map of service handoff

$Pr(\overline{OB} > R|(r,\alpha,v))$ is the conditional probability that the mobile node service termination point B locates out of the original cell's coverage, given a particular call origination point (r,α) and user's velocity v. Suppose the user's velocity v is distributed with density function $f_V(v)$, and it is independent of (r,α). Hence, the probability of service handoff is,

$$\begin{aligned} P_{ho} &= (\overline{OB} > R) \\ &= \int_0^{2\pi}\int_0^R\int_v P\{\overline{OB} > R|(r,\alpha,v)\}f(r,\alpha,v)dvdrd\alpha \quad (1) \end{aligned}$$

where $f(r,\alpha,v) = f_{X,A}(r,\alpha) * f_V(v)$.

From Fig.1, we can derive $\overline{OB} = \sqrt{r^2 + v^2t^2 - 2vt\cos\theta}$, consequently, we obtain,

$$\overline{OB} > R \Rightarrow t > \frac{r\cos\theta + \sqrt{R^2 - r^2\sin^2\theta}}{v} \quad (2)$$

Let $t_0 = \frac{r\cos\theta + \sqrt{R^2 - r^2\sin^2\theta}}{v}$, rewrite the conditional probability $P\{\overline{OB} > R|(r,\alpha,v)\}$, we get the following form,

$$\begin{aligned} P\{\overline{OB} > R|(r,\alpha,v)\} &= \int_0^{2\pi}\int_{t_0}^{\infty}\frac{\mu e^{-\mu t}}{2\pi}dtd\theta \\ &= \frac{1}{2\pi}\int_0^{2\pi} e^{-\mu t_0}d\theta \quad (3) \end{aligned}$$

Substituting (3) into (1) yields

$$P_{ho} = \int_0^{2\pi}\int_0^R\int_v \frac{e^{-\mu t_0}}{\pi R^2} r f_V(v)dvdrd\theta \quad (4)$$

Thus we get the close form of service handoff probability, which is complex, and related with users' velocity distribution, service duration and cell radius. Fortunately, some properties of the function can be deduced by the theory of convex optimization and are given by the following theorem, which is proved in Appendix B.

Theorem 1 *P_{ho} is a convex function of radius R; It is monotonically decreasing in R, and monotonically increasing in μ; Given a constant velocity v (all the users have the same velocity v), it is monotonically increasing in v.*

P_{ho} is bounded by $[0,1]$, and derivable, so we can use numerical methods to calculate it and its first-order derivative efficiently.

B. Dynamic Energy Efficiency Function

Energy-efficiency metric of cellular networks in this paper is defined as:

$$Q = \frac{\sum_{m=1}^{M} C_m/B_m}{\sum_{m=1}^{M} P_m} \quad (5)$$

where M is the total number cells in the network, P_m and C_m/B_m are the power consumption and spectral efficiency(SE) of cell m respectively. Given bandwidth, this function is equivalent with the traditional EE function, thus the total bits can be transmitted per Joule. While the power is fixed, this function is reduced to the traditional SE function, that is the data rate transmitted per Hertz. $C_m = B_m\log_2(1 + P_{rx}/N)$ is Shannon capacity, where N is defined as the noise plus interference which can be approximately seen as white noise when optimal distributed scheduling is using for large scale networks [8] and P_{rx} is the receive power, which is related with the location of the receiver's location and can be written as:

$$P_{rx}(r) = G(r)P_T = \frac{C_{att}G_{ant}G_{sf,min}}{r^{\alpha}}P_T \quad (6)$$

where $G(r)$ is the channel gain, P_T is the transmit power, C_{att} is the attenuation constant, r is the distance from the mobile user to the base station, α is the attenuation factor and usually larger than 3, G_{ant} is the antenna gain and $G_{sf,min}$ is the minimum shadow fading gain[5]. Suppose the receiver sensitivity is P_R, the transmit power should be no less than $P_R/G(R)$ to cover the users at the edge of the cell. In the following part of this paper, we use $P_T = P_R R^{\alpha}/(C_{att}G_{ant}G_{sf,min})$ as the transmit power of the base station which is just determined by the cell's radius R when P_R is given.

The power consumption of base station consists of two parts, the static power consumption which is independent of the load situation and can be seen as a constant for a given type of base station, and the dynamic power consumption part which is almost linear with the load[9]. So the total power consumption can be written as:

$$P = P_s + P_T/\eta \quad (7)$$

where η is a constant and determined by the power amplifier efficiency, power supply and feeder loss etc.

Suppose the cellular network is homogeneous, which means all the cells have the same parameters and load condition. Consider the saturation condition, under which a service requirement can arrive anywhere in the cell, so we use the expected SE of the networks to replace the numerator of (5), and can be written as:

$$SE = E_{r,\theta}\{\log_2(1+\frac{P_{rx}(r)}{N})\}$$
$$= 2\int_0^1 \log_2(1+\frac{P_R}{N}x^{-\alpha})xdx \quad (8)$$

where $E_{r,\theta}$ is the expectation of UE's location. From (8) we can see SE is a constant and is only related with P_R and N, independent of cell's radius R.

Resources should be reserved for the handoff users to prevent the interruption of the on-going service. Under the ideal conditions, the percentage of reserved resource is equal to P_{ho}, means the SE of the cell should be multiplied by a factor $1-P_{ho}$. At the same time, the reduction of the effective load leads the consumption of dynamic power decreasing proportionally[9]. Hence, we get the *dynamic energy efficiency function* $Q_{ho}(R)$, with respect to user's handoff and service duration:

$$Q_{ho}(R) = \frac{(1-P_{ho})SE}{P_s + P_T(1-P_{ho})/\eta} \quad (9)$$

where SE is defined in (8).

If the maximal handoff blocking probability of the network is limited to P_{block}, the effective EE of the network can be rewritten by replacing P_{ho} with $P_{block} * P_{ho}$ in (9) easily. The closed form of DEE can not only reveal the relationship between the user's mobility characteristics and the effective EE, but also reflect the influence of the service distribution to the effective EE of the network.

III. Problem Formulation and Optimal Energy-Efficient Cell Design

The energy saving problem in access networks is formulated to maximize the DEE function by adjusting transmit power or equivalently changing R while considering the system maximal transmit power limitation, as follows:

$$\max_{R} \quad Q_{ho}(R) \quad (10)$$
$$s.t. \quad P_T \le P_{Tmax} \quad (11)$$

where P_{Tmax} in (11) is the maximum transmit power of the base station.

We can solve constraint (11) directly, resulting in $R \le R_{max}$, which is a convex set, where $R_{max} = P_{Tmax}C_{att}G_{ant}G_{sf,min}/P_R$. The objective function $Q_{ho}(R)$ is a fractional function and couldn't be solved directly, but we have the following theorem which is proved in Appendix C.

Theorem 2 *$Q_{ho}(R)$ is a concave function and there exists one and only one optimal value $R^* \in (0,\infty)$ making it maximal.*

From Theorem 2, the optimal cell size R which maximization the total DEE of the network is:

$$R_{opt} = \begin{cases} R^* & \text{if } R^* \le R_{max} \\ R_{max} & \text{else} \end{cases} \quad (12)$$

TABLE I
Energy-Efficient Cell Design Algorithm

Step 1: Initialization
Get the mobility characteristics function $f_V(v)$ and the average service duration μ
Step 2: Using Gradient Method to Obtain the Optimal Cell size
(1) $i = 0$, select $\forall R_0 > 0$ as starting radius, denote the $SE/Q_{ho}(R)$ as $Q_{inv}(R)$.
(2) Calculate $P_{ho}(R_i)$ and its first derivative using (4) by *trapezium formula* [11].
(3) Calculate $Q_{inv}^{'}(R_i)$ and its first derivative.
(4) Line search. Choose step size t via backtracking line search [12].
(5) Update $R_{i+1} = R_i - tQ_{inv}^{'}(R_i)$.
(6) Repeat (2)-(5) until the stopping criterion is satisfied, then we can get the optimal R^* and the optimal cell radius $R_{opt} = \min\{R^*, R_{max}\}$
Step 3: Adjust the Transmit Power
According to the results in Step 2, adjust the send power as $P_{T,opt} = P_R R_{opt}^{\alpha}/(C_{att}G_{ant}G_{sf,min})$

We should notice that the users' mobility and service characteristics can be directly measured in the coverage area by the operator. Thus, the optimal DEE can be achieved by adjusting the cell's size R when deploy the base stations. For the existing networks, the base station can adjust the transmit power to reach the optimal cell radius according to user's service density, like Cell-Zooming in [10] which didn't consider user's mobility, while we consider it here.

Table I gives the algorithm to calculate the optimal cell size R_{opt} and corresponding optimal transmit power $P_{T,opt}$. Due to the concavity of function $Q(R)$, efficient numerical method can be used to solve the optimal problem such as gradient descent method, Newton's method etc. In this paper, *Trapezium formula* [11] is used to calculate P_{ho} and its first-order derivation, and we use gradient descent method to get the global optimal points.

IV. Numerical Results

In this section, we demonstrate the relationship between DEE and cell radius R with different user's mobility and service characteristics. The system parameters are listed in Table II. The channel type is Okuhata model[5], and the power model is referred to [13]. Suppose the maximal transmit power of the base station P_{Tmax} is 55dBm. The users' average speed vary between $1m/s$ to $30m/s$, representing from walking speed to high-speed railway's velocity. In our simulation, we use the uniform distribution of v, thus $f_V(v) = \frac{1}{2\overline{v}}$. The following curves relating to R are plotted in semi-logarithmic coordinates.

In Fig.2 we see the relation between probability of service handoff and the cell radius with regard to (4) for different user's velocity distributions and service durations where $\overline{v_1} = 5m/s$, $\overline{v_2} = 15m/s$, $\overline{v_3} = 25m/s$ and $\mu_1^{-1} = 2min$, $\mu_2^{-1} = 4min$. Here we don't consider the limitation of maximal transmit power. For each $\overline{v}$, μ^{-1}, we can observe an equal relation, that the P_{ho} decreases with cell radius R, μ and increases with $\overline{v}$, which are consistent with Theorem 1.

TABLE II
PARAMETER SETTINGS

Parameter	Value
Carrier frequency	2.4 GHz
Path loss factor α	3.5
Attenuation constant C_{att}	-30 dB
Antenna gain G_{ant}	7 dB
Minimum shadow fading gain $G_{sf,min}$	-8 dB
Bandwidth	5 MHz
Thermal noise N_0	-174 dBm/Hz
Interference N_I	-150 dBm/Hz
Receiver sensitivity P_R	-100 dBm
Average velocity $\overline{v}$	1-30 m/s
Average service duration μ	1-10 min
Static power consuming P_s	68.73 W
Efficiency factor η	0.26
Maximal transmit power P_{Tmax}	55dBm

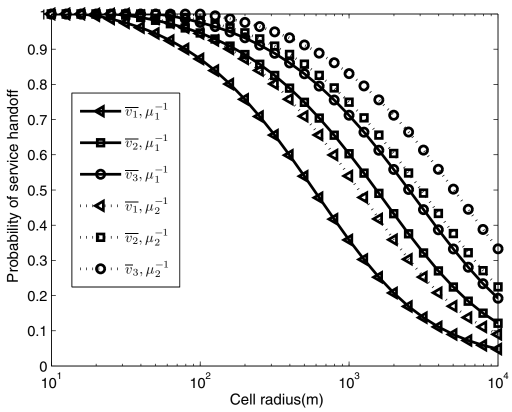

Fig. 2. Probability of service handoff P_{ho} vs. cell radius R with different average velocity $\overline{v}$ and service duration μ^{-1}

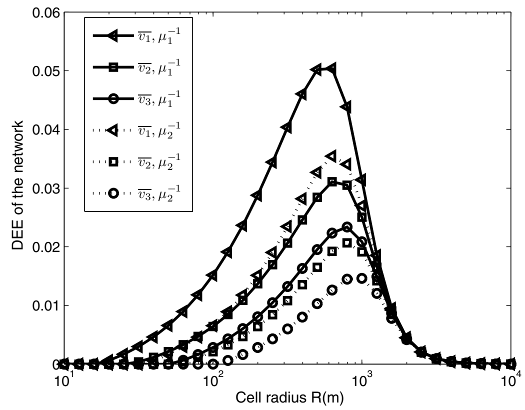

Fig. 3. Dynamic Energy-efficiency value Q_{ho} of the network vs. cell radius R with different average velocity $\overline{v}$ and service duration μ^{-1}

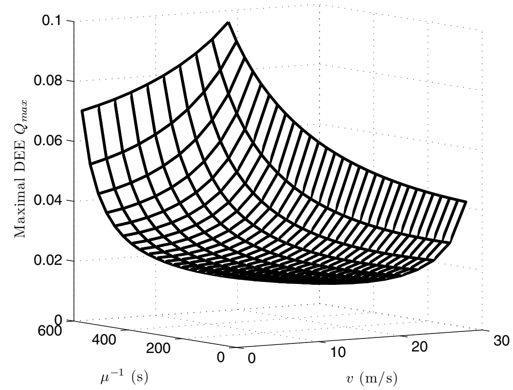

Fig. 4. Optimal DEE value Q_{ho} vs. various $\overline{v}$ from $1m/s$ to $30m/s$ and various μ^{-1} from $1min$ to $10min$

The DEE of the networks as function of cell radius R for different $\overline{v}$, and μ^{-1} is depicted in Fig.3 and constraint (11) is not considered here too. It can be observed that for each $\overline{v}$, μ^{-1}, the DEE has an maximum point and the maximal value is decreasing with increasing $\overline{v}$ and μ^{-1} which is consistent with Theorem 2. The value of DEE is increasing firstly due to the reducing of reserving resources and begins decreasing from the optimal radius R_{opt} due to the transmit power should be increase linearly with R^α to cover the edge user where the effect of P_{ho} is slight. Also we can find that the optimal cell radius is increasing with user's moving speed and service duration. The reason is that the larger is v, μ^{-1}, the larger is P_{ho}, thus more resources should be reserved to avoid blocking the handoff service. To improve the DEE of the network serving high speed or long service duration users, the base station should enlarger the transmit power which is equivalent to enlarger the cell radius.

Fig.4 and Fig.5 illustrate the maximal DEE and the according optimal R_{opt} with various $\overline{v}$ and μ^{-1}. We can see that the properties is demonstrated again, Fig.4 shows apparently that the maximal DEE decreases with increasing $\overline{v}$ and μ^{-1} while in Fig.5 the optimal cell size R_{opt} is increasing with $\overline{v}$ and μ^{-1}. But the R_{opt} become constant and equal to $1807m$ while the $\overline{v}$ and μ^{-1} increasing to some definite value due to the constraint (11). From Fig.5 it is easy to obtain that for the macro coverage, the cell's radius should be no less than $500m$ to reach the optimal energy-efficient point. And while the cells whose user's mobile speed is low, the optimal cell size is not larger than 1500m, for example, when $\overline{v} = 1m/s$, $\mu^{-1} = 2min$, we have $R_{opt} = 686m$.

V. CONCLUSION

In this paper, we investigate the energy efficiency coverage of cellular networks while considering users' mobility and service characteristics. We introduce the the concept of dynamic energy efficiency function which considers service handoff as the system performance metric. An unique globally optimal cell size is obtained for energy-efficient coverage of homogeneous networks by analyzing the DEE function. From the numerical results, we observed that the optimal cell size should be large enough to reduce the probability of service handoff while the average moving speed is high or the average service duration is long. This work can be used for network

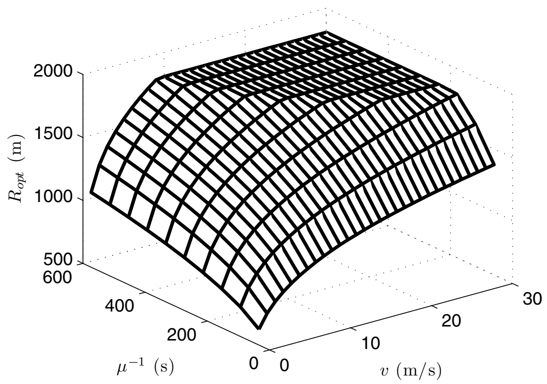

Fig. 5. Optimal cell radius R vs. various $\overline{v}$ from $1m/s$ to $30m/s$ and various μ^{-1} from $1min$ to $10min$

planning and energy saving by dynamic adjusting cell size for low load conditions.

ACKNOWLEDGMENT

This work is supported by NSFC(61172088), National programs for High Technology Research and Development (SS2012AA011702) and CMCC T-Ring Project (2011).

APPENDIX A
SOME IMPORTANT LEMMAS

Some important lemmas for convex optimization are given below, proofs are omitted due to space. All of them can be found in [12].

Lemma 1 *If function f is positive and convex, then $1/f$ is concave; If it is positive and concave, then $1/f$ is convex.*

Lemma 2 *If $f(x, y)$ is convex in x for each $y \in A$, and $w(y) > 0$ for each $y \in A$, then the function g defined as $g(x) = \int_A w(y)f(x, y)dy$ is convex in x (provided the integral exists).*

APPENDIX B
PROOF OF THEOREM 1

Proof: Let $r = Rx$, $dr = Rdx$, then we can rewrite (4) as

$$P_{ho}(R) = \int_0^{2\pi}\int_0^1\int_v g_{x,\theta,v}(x, \theta, v, R)xf_V(v)dvdrd\theta \quad (13)$$

where $g_{x,\theta,v}(x, \theta, v, R) = e^{-\mu R[x\cos\theta+\sqrt{1-x^2\sin^2\theta}]/v}$ is continuous derivable. The second derivative of $g_{x,\theta,v}(x, \theta, v, R)$ with R is

$$\frac{\partial^2 g_{x,\theta,v}(x, \theta, v, R)}{\partial^2 R} = \left(\frac{\mu}{v}\left[x\cos\theta + \sqrt{1 - x^2\sin^2\theta}\right]\right)^2 * g_{x,\theta,v}(x, \theta, v, R) \geq 0 \quad (14)$$

So given (x, θ, v) in the definition domain which is a convex set, $g_{x,\theta,v}(x, \theta, v, R)$ is convex. Thus according to Lemma 2 in Appendix A, $P_{ho}(R)$ is convex since $x \geq 0$ and $f_V(v) \geq 0$.

Consider the integrand of $P_{ho}(R)$, given any $R_1 < R_2$, $g_{x,\theta,v}(x, \theta, v, R_1) > g_{x,\theta,v}(x, \theta, v, R_2) > 0$ and the integrating range is positive, so $P_{ho}(R)$ is monotonically decreasing of R. Similarly, $P_{ho}(R)$ is monotonically increasing of μ and given a constant velocity v,it is monotonically increasing of v. Hence, we have Theorem 1. ■

APPENDIX C
PROOF OF THEOREM 2

Proof: The numerator and denominator in (9) are divided by $(1 - P_{ho})$ and rearrange the result, we have:

$$Q_{ho} = \frac{SE}{P_s/(1 - P_{ho}) + P_T/\eta} = \frac{SE}{f(R) + g(R)} \quad (15)$$

where $g(R) = P_T/\eta = P_R R^\alpha/(C_{att}G_{ant}G_{sf,min})$ is a convex function of R and $f(R) = P_s/(1 - P_{ho})$. From Theorem 1, P_{ho} is a convex function of R and $P_{ho} \in (0, 1)$. So $1-P_{ho}$ is concave and $1-P_{ho} > 0$. Using Lemma 1, $g(R)$ is convex and greater than 0. The sum of two convex function is also a convex function. Using Lemma 1 again, $\frac{SE}{f(R)+g(R)}$ is concave.

$\lim_{R->0} R_{ho}(R) = 0$, $\lim_{R->\infty} R_{ho}(R) = 0$ and $\forall R_0 < \infty$, $Q_{ho}(R_0) > 0$, so there must exist a $R^* < \infty$, where the $Q_{ho}(R)$ reach maximization. Due to the concavity of $Q_{ho}(R)$, there is only one optimal R^*. Hence, we have Theorem 2. ■

REFERENCES

[1] P. G, Fettweis and E. Zimmermann, ICT energy consumption - trends and chanllenges, *Proceedings of the 11th International Symposium on Wireless Personal Multimedia Communication*, Lapland,Finland, 2008.

[2] F. Richter, A. J. Fehske, and G. P. Fettweis, Energy Efficiency Aspects of Base Station Deployment Strategies for Cellular Networks, *IEEE 70th Vehicular Technology Conference Fall (VTC 2009-Fall)*, pp. 1-5, 2009.

[3] Z. Niu, TANGO: traffic-aware network planning and green operation, *IEEE Wireless Communications*, vol. 18, pp. 25-29, 2011.

[4] Eunsung Oh, Bhaskar Krishnamachari, Energy Savings through Dynamic Base Station Switching in Cellular Wireless Access Networks, *2010 IEEE Global Telecommunications Conference*, pp. 1-5, 2010

[5] M. Ericson, Total Network Base Station Energy Cost vs. Deployment, *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 2011.

[6] H. Klessig, A. J. Fehske, and g. P. Fettweis, Energy efficiency gains in interference-limited heterogeneous cellular mobile radio networks with random micro site deployment, *2011 34th IEEE Sarnoff Symposium*, pp. 1-6, 2011.

[7] G. Qiang and H. Cherng-shung, Mobility based estimation of inter-BSC soft handoff characteristics in CDMA networks, *IEEE Wireless Communications and Networking, WCNC 2003*, pp. 1202-1206 vol.2, 2003.

[8] S. G. Kiani and D. Gesbert, Optimal and Distributed Scheduling for Multicell Capacity Maximization, *IEEE Transactions on Wireless Communication*, vol. 7, pp. 288-297, 2008.

[9] G. Auer, V. Giannini, C. Desset, et al, How much energy is needed to run a wireless network?, *IEEE Wireless Communications*, vol. 18, pp. 40-49, 2011.

[10] Xiangnan Weng, Dongxu Cao, and Zhisheng Niu, Energy-Efficient Cellular Network Planning under Insufficient Cell Zooming, *IEEE 73rd Vehicular Technology Conference (VTC Spring)*, pp. 1-5, 2011.

[11] Willam. H. Press. et al, *Numerical Recipes in C++:The art of Scientific Computing*, Cambridge University Press, 2002.

[12] L. V. Stephen boyd, *Convex Optimization*, Cambridge Univ. Press, 2004

[13] O. Arnold, F Richter, G. Fettweis, and O. Blume, Power consumption modeling of different base station types in heterogeneous cellular networks, *Future Network and Mobile Summit*, pp. 1-8, 2010.