On Metrics and Models for Energy Efficient Design of Wireless Access Networks

Sibel Tombaz, Ki Won Sung, and Jens Zander

***Abstract*—The energy efficiency of wireless access networks has attracted significant interest, due to escalating energy cost and environmental concerns. How energy efficiency should be measured is, however, still disputed in the literature. In this letter, we discuss the impact of performance metrics and energy consumption models in network dimensioning. We argue that using a popular metric, the number of bits/Joule, may give misleading results, unless the capacity and coverage requirements of the system are carefully defined. We also claim that the energy consumption in the backhaul and the idle power of the base stations have to be taken into account. To support our claims, we demonstrate in a simple example how misleading results can be obtained by using flawed performance metrics.**

***Index Terms*—Energy efficiency, wireless access network, performance metric, power consumption model, network deployment.**

I. Introduction

With the soaring cost of energy and increasing concern for environment, the energy efficiency in wireless networks has been a hot research topic over the last few years. However, the direction for energy efficient network design is still debatable. Let us take an example of a network dimensioning problem. Densification and small cell deployment were suggested as promising solutions for significant energy savings in [1], [2], whereas [3], [4] claimed the opposite. One of the main reasons behind the contradictory results is that the studies employed different assumptions. Indeed, there exist various performance metrics and energy consumption models in the literature (see Section 2). Therefore, it is important to understand how different results can be obtained by employing different sets of metrics and models.

In this letter, first we review performance metrics and energy consumption models widely accepted in energy efficiency studies. Then, we discuss the impact of using different sets of metrics and models on the dimensioning of energy efficient networks. In order to make the discussion quantitative, we take a simple optimization problem as an example; the problem to find the optimal cell size that maximizes the energy efficiency for a homogeneous cellular network.

Our main contribution is to identify key aspects that should be considered when solving the network dimensioning problem for energy efficient networks. We demonstrate that both coverage and capacity requirements must be considered in order to avoid contradictory conclusions by different metrics. We also argue that a precise characterization of the network power consumption is essential. Simply considering the radiated power of the base stations (BSs) and neglecting other features such as backhaul and idle power consumption of BSs results in misleading conclusions.

S. Tombaz, K.W. Sung (corresponding author), and J. Zander are with the Department of Communication Systems, KTH Royal Institute of Technology, Stockholm, Sweden, e-mail: sibel@kth.se, sungkw@kth.se, jenz@kth.se.

II. Review of Performance Metrics and Energy Consumption Models

In this section, we describe most widely used performance metrics and energy consumption models. We consider a homogeneous cellular network in the description. For brevity, we assume that the energy consumption of the network is time-invariant. Thus, time index is neglected hereafter.

A. Energy Efficiency Metrics

bit/Joule: This is the most commonly used metric in particular for the evaluation of a single wireless link [5]. Its use has naturally been extended to the assessment of the whole wireless access network [4], [6]–[8]. Let Ψ denote the bit/Joule efficiency of the network. Then, it can be written as below:

$$\Psi = \frac{C_{net}}{P_{net}}. \tag{1}$$

Here, C_{net} is defined as the aggregate network capacity in bits/s, and P_{net} is the total power consumption of the network in watts.

W/km^2: Another widely accepted energy efficiency metric is the area power consumption denoted by Ω [3], [9]–[11]. It relates the total power consumption of the network (P_{net}) to the size of the covered area ($\mathcal{A}$) and is given by

$$\Omega = \frac{P_{net}}{\mathcal{A}}. \tag{2}$$

Note that the optimal energy efficiency is achieved when the metric is maximized with respect to bit/Joule, or minimized in terms of W/km^2.

B. Network Power Consumption Model

In a homogeneous cellular system, the power consumption of the access network, P_{net}, is considered to be the sum of power consumed by base stations. That is,

$$P_{net} = N_{BS} P_{BS}, \tag{3}$$

where N_{BS} is the number of deployed base stations in $\mathcal{A}$, and P_{BS} is the power consumption of a base station. Thus, modeling of P_{net} boils down to the characterization of P_{BS}.

Model 1: Many previous studies regarded the radiated power of the base stations as the only accountable part of the power consumption [1], [12], [13]. Model 1 can be simply written as

$$P_{net} = N_{BS} P_{tx} \tag{4}$$

where P_{tx} denotes the radiated transmission power of a base station.

Model 2: According to [9], the power consumption of a base station can be divided into two parts: (i) traffic-invariant consumption, i.e., the power the base station spends even when there is no transmission; (ii) traffic-related consumption. This means that

$$P_{BS} = a\,P_{tx} + b. \tag{5}$$

Here, the coefficient a accounts for the power consumption which is proportional to the radiated power (e.g., radio frequency (RF) amplifier power including feeder losses), and b denotes the power independent of the transmission (e.g., signal processing, site cooling) [9]. This model has recently obtained popularity [11], [14], [15].

In [16], [17], the model was extended by acknowledging that the backhaul is also an important source of traffic-invariant consumption. By letting P_{bh} denote the backhaul power consumption per base station, P_{net} can be described as follows:

$$P_{net} = N_{BS}(a\,P_{tx} + b + P_{bh}). \tag{6}$$

The backhaul power P_{bh} includes not only the downlink and the uplink power consumption (i.e., from a base station to the aggregation switch(es) and from the switch(es) to the aggregation network, respectively) but also the power consumed at the aggregation switch(es), which is proportional to the total traffic backhauled from the mobile network. A detailed expression for P_{bh} can be found in [16].

III. Energy efficient network dimensioning problem

In this section, we present a dimensioning problem aiming at either maximizing Ψ (bit/Joule) or minimizing Ω (W/km^2). Our main objective is to illustrate how the selection of performance metrics and power consumption models affects the solution of the problem.

A. System Model

We consider a homogeneous network deployment that is organized in a hexagonal layout with a tunable cell range R covering a compact region $\mathcal{S} \subseteq \mathbb{R}^2$ with $\mathcal{A}$ km^2, i.e., $\mathcal{A} = |\mathcal{S}|$. Despite the fact that BS types can be arbitrary, in this paper we consider deployments with macro BSs equipped with omni-directional antennas. Then, we have $N_{BS} = \frac{2\mathcal{A}}{3\sqrt{3}R^2}$.

In the downlink direction, the received signal power at distance d from a base station can be modeled by

$$P_{rx}(d) = \frac{cGP_{tx}}{d^{\alpha}}, \tag{7}$$

where c and α are the path loss coefficient and exponent, respectively, and G is the antenna gain. Then, the downlink signal-to-interference plus noise ratio (SINR) denoted by $\Gamma(d)$ can be obtained via a fluid model [18]. If we assume that the coverage area is large enough, the SINR of a cell edge user, i.e., $d = R$, can be written as

$$\Gamma(R) = \frac{1}{\frac{4\pi}{3\sqrt{3}(\alpha-2)}(\sqrt{3}-1)^{2-\alpha} + \frac{N_0 W}{cGP_{tx}}R^{\alpha}}. \tag{8}$$

Let C_{cell} denote the cell capacity. Then, under the full-buffer traffic model assumption where each BS has at least one mobile requesting data with all resources allocated, C_{cell} is obtained by inserting (8) to Shannon's formula, i.e., $C_{cell} = W\,\log_2(1+\Gamma(R))$. Note that here, for simplicity, the cell capacity is defined for the worst case scenario where the user stands at the cell edge. Therefore, the achievable network capacity defined as the sum of cell capacities within the network area can be written as

$$C_{net} = N_{BS}\,W\,\log_2\left(1+\frac{1}{\frac{4\pi}{3\sqrt{3}(\alpha-2)}(\sqrt{3}-1)^{2-\alpha} + \frac{N_0 W}{cGP_{tx}}R^{\alpha}}\right). \tag{9}$$

B. Problem Formulation

Our objective is to optimize the energy efficiency by maximizing Ψ (bit/Joule) or minimizing Ω (W/km^2), under the full network coverage constraint which ensures that the received power of any user in a given cell is above a given threshold, P_{min}. The design variable of this problem is defined as number of BSs in the area. In order to illustrate the impact of using different sets of metrics and models, we consider two different problem formulations as below:

Problem 1: No requirement for network capacity
The capacity requirement is not considered in the optimization problem:

$$\begin{aligned} \underset{N_{BS}}{\textbf{Optimize}} \quad & \Psi \text{ or } \Omega \\ \textbf{subject to} \quad & P_{rx}(N_{BS}) \geq P_{min}. \end{aligned} \tag{10}$$

Problem 2: There is a target network capacity
The optimization process is subject to a predefined network capacity target, C_{target}, as below:

$$\begin{aligned} \underset{N_{BS}}{\textbf{Optimize}} \quad & \Psi \text{ or } \Omega \\ \textbf{subject to} \quad & P_{rx}(N_{BS}) \geq P_{min}, \\ & C_{net} = C_{target}. \end{aligned} \tag{11}$$

IV. Numerical results

In this section, we present the solutions of the optimization problems introduced in (10) and (11) by considering different energy efficiency metrics and power consumption models.

Observation 1 *When the capacity requirement is not taken into account, different metrics lead to contradictory conclusions.*

This observation can be mathematically formulated in the following proposition.

Proposition 1 *Let N^*_{Ψ} and N^*_{Ω} denote the optimum number of BSs for Problem 1 with respect to bit/Joule and W/km^2, respectively. Then, $N^*_{\Psi} \neq N^*_{\Omega}$ and $N^*_{\Psi} = \infty$.*

Proof: Firstly, we choose P_{tx} as the minimum transmit power required to ensure full coverage, i.e., $P_{tx} : P_{rx}(R) = P_{min}$. This also represents the optimum transmit power for interference limited systems considering that energy consumption is strictly increasing with the transmit power. Therefore, the functional relationship between the transmit power and the number of BSs can be written using Eq. (7) as

$$P_{tx}(N_{BS}) = \left(\frac{2\mathcal{A}}{3\sqrt{3}}\right)^{\alpha/2} \frac{P_{min}}{cG}\, N_{BS}^{-\alpha/2}. \tag{12}$$

Note that this relationship holds regardless of the energy efficiency metric and the power consumption model. Based on the given relationship, we define N^*_Ψ and N^*_Ω considering *Problem 1* as follows.

When we aim to define the optimum number of BSs using the W/km^2 metric, the objective function will have the following dependence on number of BSs:

$$\Omega(N_{BS}) = \frac{N_{BS}\left[aP_{tx}(N_{BS}) + b + P_{bh}\right]}{\mathcal{A}} \approx f_1(N_{BS}^{1-\alpha/2}) + f_2(N_{BS}) \quad (13)$$

Here $f_1(.)$, and $f_2(.)$ denote the relationship between each term of Ω and N_{BS}. It is clear that $\Omega(N_{BS})$ is a unimodal function, $\forall \alpha > 2$, since, while $f_1(N_{BS}^{1-\alpha/2})$ is monotonically decreasing with N_{BS}, $\forall\, \alpha > 2$, $f_2(N_{BS})$ is monotonically increasing. Therefore, the solution of *Problem 1* indicates that there is always a non-null and finite number of BSs minimizing the W/km^2 measure when *Model 2* is employed; i.e., $N^*_\Omega \neq \infty$.

On the other hand, when the objective of *Problem 1* is changed to maximizing Ψ expressed in bit/Joule, we can write the objective function as follows:

$$\Psi = \frac{N_{BS}\, W \log_2(1 + \Gamma(R))}{P_{net}(N_{BS})}. \quad (14)$$

Here, the SINR of a cell edge user $\Gamma(R)$ can be obtained by inserting (12) to (8) as

$$\Gamma(R) = \frac{1}{\frac{4\pi}{3\sqrt{3}(\alpha-2)}(\sqrt{3}-1)^{2-\alpha} + \frac{N_0 W}{P_{min}}}. \quad (15)$$

Considering the fact that P_{min} is predefined and constant, (15) reveals that the SINR distribution is independent of N_{BS} as long as the transmit powers of the BSs are scaled with the densification.

Based on the given relationships in (12) and (15), we observe that Ψ becomes a non-decreasing function of N_{BS}, i.e., $\frac{\partial C_{net}}{\partial N_{BS}} > \frac{\partial P_{net}}{\partial N_{BS}}$, regardless of the considered power consumption model. Therefore, the solution of *Problem 1* indicates that infinite densification is required in order to maximize the bit/Joule metric, i.e., $\Psi \to \infty$ when $N \to \infty$ and thus $N^*_\Psi = \infty; N^*_\Psi \neq N^*_\Omega$ □

This observation is illustrated in Fig. 1 which depicts the variation of the bit/Joule and W/km^2 metrics as function of the number of BSs when the capacity requirement is not considered. It should be noted that for the numerical analysis, macro type base stations are considered where a = 4.7 and b = 130 [9], whereas backhaul power consumption P_{bh} is calculated based on [16]. We observe in Fig. 1 that bit/Joule is monotonically increasing with network densification. On the contrary, the W/km^2 metric indicates that reduced transmit power cannot compensate the additional power consumption for backhaul and idle state. Therefore, the W/km^2 metric increases with number of BSs after reaching the optimum point. This suggests that maximizing the energy efficiency is not always equivalent to minimizing the energy consumption. Therefore, the capacity requirement must be considered in order to prevent contradictory conclusions with different metrics.

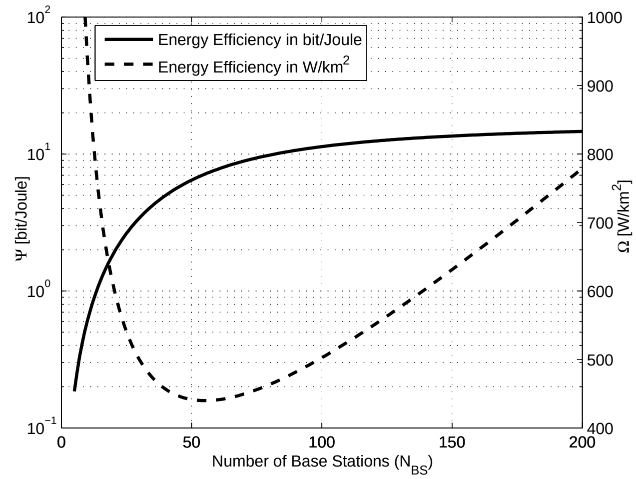


Fig. 1. Bit per joule, area power consumption vs. number of base stations for Problem 1 (Model 2 is considered). The parameter settings: $\mathcal{A}$=41 km^2, α=3.5, P_{min}=-70 dBm, W=5 MHz.

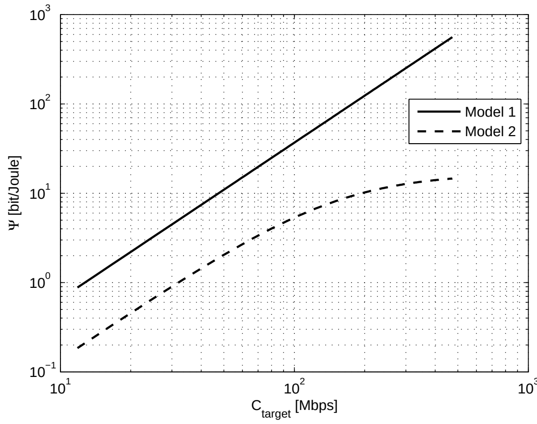
Observation 2 *Considering only radiated power to assess the power consumption leads to a misleading conclusion even when the optimization problem has well defined coverage and capacity constraints.*

This observation can be mathematically stated in the following proposition.

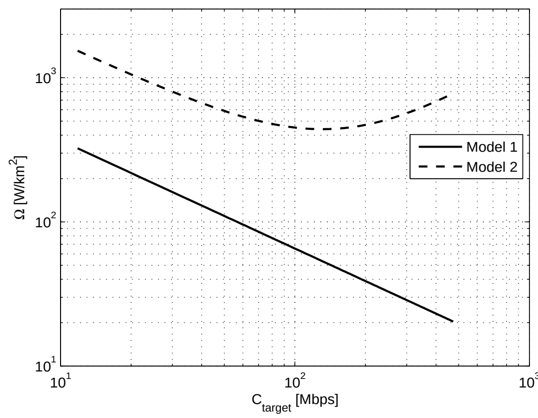
Proposition 2 When $P_{BS} = P_{tx}$ and $C_{target} \to \infty$, $\Psi \to \infty$ and $\Omega \to 0$, $\forall\, \alpha > 2$.

Proof: When the network capacity requirement is settled as in *Problem 2*, i.e, $C_{net} = C_{target}$, there is a unique number of base stations optimizing the energy efficiency with respect to both bit/Joule and W/km^2, i.e., $N^*_\Psi = N^*_\Omega = \frac{C_{target}}{C_{cell}}$. This optimal number monotonically increases with the target network capacity C_{target} since C_{cell} is independent of N_{BS}. On the other hand, based on (12), the transmit power decreases with number of BSs proportional to $N_{BS}^{-\alpha/2}$. Therefore, when *Model 1* is used to assess the power consumption, the optimal energy efficiency with respect to the bit/Joule and W/km^2 metrics have the following relationships: $\Psi^* = \frac{C_{net}}{N^*_\Psi\, P_{tx}} = C_{cell} \times (\frac{2\mathcal{A}}{3\sqrt{3}})^{-\alpha/2} \frac{cG}{P_{min}} (N^*_\Psi)^{\alpha/2} = \kappa \times (N^*_\Psi)^{\alpha/2}$ and $\Omega^* = \frac{N^*_\Omega\, P_{tx}}{\mathcal{A}} = \frac{N^*_\Omega}{\mathcal{A}} (\frac{2\mathcal{A}}{3\sqrt{3}})^{\alpha/2} \frac{P_{min}}{cG} (N^*_\Omega)^{-\alpha/2} = \beta \times (N^*_\Omega)^{1-\alpha/2}$. Here κ, and β denote the constant terms in the expressions of Ψ^* and Ω^*, respectively. Based on the introduced relationships, we observe that the energy efficiency always increases with higher capacity requirement, when the idle power and the backhaul impact are ignored, i.e., $C_{target} \to \infty$, then $N^*_\Psi = N^*_\Omega \to \infty$. Thus, $\Psi^* \to \infty$ and $\Omega^* \to 0$, $\forall\, \alpha > 2$. □

The observation is demonstrated in Fig. 2 which shows the optimum energy efficiency as a function of the capacity requirement of the network. We can clearly see that a higher capacity requirement results in improved energy efficiency for both metrics when Model 1 is employed, i.e. the radiated power is the only source of network power consumption. However, it is obvious that the decrease in radiated power is not beneficial if it comes at the expense of a higher traffic-invariant power consumption. This is reflected in Fig. 2(b)



(a) Energy efficiency in bit/Joule versus target network capacity.



(b) Energy efficiency in W/km^2 versus target network capacity.

Fig. 2. Relationship between energy efficiency and target network capacity considering different metrics and models for Problem 2. The parameter settings: $\mathcal{A}$=41 km^2, α=3.5, P_{min}=-70 dBm, W=5 MHz.

where the area power consumption starts increasing beyond a certain target network capacity when Model 2 is taken into consideration.

We also observe that using the bit/Joule or W/km^2 metrics do not lead to a contradictory conclusion when both coverage and capacity requirements are well defined and a realistic network power consumption model is employed. Therefore, we argue that the characterization of the coverage and capacity requirements and the incorporation of backhaul and idle power consumption are the key aspects of preventing a misleading conclusion for the energy efficient network dimensioning problem.

V. Conclusions

In this letter, we discussed the impact of performance metrics and power consumption models on the energy efficient network dimensioning problem. To this end, we first review the metrics and the models widely accepted in the energy efficiency studies. We use a simple network dimensioning problem where the objective is to find the optimal base station density maximizing energy efficiency in order to demonstrate the impact of using different set of metrics and models.

We showed that when the energy efficient network dimensioning problem does not have well defined coverage and capacity constraints, different metrics indicate contradictory conclusions. This clearly shows that maximizing the energy efficiency is not equivalent to minimizing the energy consumption unless capacity and coverage requirements of the system are carefully considered. Furthermore, we demonstrated that the precise characterization of the power consumption of the network is essential since ignoring the idle power will lead misleading conclusions. In order to avoid the debatable directions for energy efficient network design, these key aspects have to be considered.

References

[1] T. Le and M. Nakhai, "Possible power-saving gains by dividing a cell into tiers of smaller cells," *Electronics Letters*, vol. 46, no. 16, pp. 1163 –1165, May 2010.

[2] H. Claussen, L. Ho, and F. Pivit, "Effects of joint macrocell and residential picocell deployment on the network energy efficiency," in *Proc. of IEEE Personal, Indoor and Mobile Radio Commun. (PIMRC)*, Cannes, France, Sept. 2008.

[3] M. Ericson, "Total network base station energy cost vs. deployment," in *Proc. of IEEE Vehic. Technol. Conf. (VTC Spring)*, Budapest, Hungary, May 2011.

[4] C. Khirallah, J. Thompson, and H. Rashvand, "Energy and cost impacts of relay and femtocell deployments in long-term-evolution advanced," *IET Communications*, vol. 5, no. 18, pp. 2617 –2628, Feb. 2011.

[5] G. Miao, N. Himayat, G. Li, and A. Swami, "Cross-layer optimization for energy-efficient wireless communications: a survey," *Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 529–542, 2009.

[6] H. Q. Ngo, E. Larsson, and T. Marzetta, "Energy and Spectral Efficiency of Very Large Multiuser MIMO Systems," *IEEE Transactions on Communications*, vol. 61, no. 4, pp. 1436–1449, April 2013.

[7] S. Aleksic, M. Deruyck, W. Vereecken, W. Joseph, M. Pickavet, and L. Martens, "Energy efficiency of femtocell deployment in combined wireless/optical access networks," *Elsevier Computer Networks*, vol. 57, no. 5, pp. 1217 – 1233, Apr. 2013.

[8] S. Navaratnarajah, A. Saeed, M. Dianati, and M. Imran, "Energy efficiency in heterogeneous wireless access networks," *IEEE Wireless Communications Magazine*, vol. 20, no. 5, pp. 37–43, Oct. 2013.

[9] G. Auer, V. Giannini, C. Desset, I. Godor, P. Skillermark, M. Olsson, M. Imran, D. Sabella, M. Gonzalez, O. Blume, and A. Fehske, "How much energy is needed to run a wireless network?" *IEEE Wireless Communications Magazine*, vol. 18, no. 5, pp. 40–49, Oct. 2011.

[10] M. Fallgren, M. Olsson, and P. Skillermark, "Energy saving techniques for LTE: Integration and system level results," in *Proc. of IEEE Personal, Indoor and Mobile Radio Commun. (PIMRC)*, London, UK, Sept 2013.

[11] D. Tsilimantos, J.-M. Gorce, and E. Altman, "Stochastic analysis of energy savings with sleep mode in OFDMA wireless networks," in *Proc. of IEEE Int. Conf. on Computer Communications (INFOCOM)*, Turin, Italy, Apr. 2013.

[12] H. Leem, H. Jin, and D. K. Sung, "Scaling laws of energy efficiency related metrics for varying cell radii in downlink cellular systems," *IEEE Communications Letters*, vol. 17, no. 3, pp. 525–528, March 2013.

[13] L. Zhang, H.-C. Yang, and M. Hasna, "Generalized area spectral efficiency: An effective performance metric for green wireless communications," *IEEE Transactions on Communications*, vol. 62, no. 2, pp. 747–757, Feb. 2014.

[14] A. D. Domenico, E. C. Strinati, and A. Capone, "Enabling Green cellular networks: A survey and outlook ," *Elsevier Computer Communications*, vol. 37, pp. 5 – 24, 2014.

[15] H. Holtkamp, G. Auer, S. Bazzi, and H. Haas, "Minimizing base station power consumption," *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 2, pp. 297–306, Feb. 2014.

[16] S. Tombaz, P. Monti, K. Wang, A. Västberg, M. Forzati, and J. Zander, "Impact of backhauling bower consumption on the deployment of heterogeneous mobile networks," in *Proc. of IEEE Global Comm. Conf. (GLOBECOM)*, Houston, USA, Dec. 2011.

[17] S. Tombaz, P. Monti, F. Farias, M. Fiorani, L. Wosinska, and J. Zander, "Is backhaul becoming a bottleneck for green wireless access networks?" in *Proc. of IEEE Int. Conf. Comm. (ICC)*, Sydney, Australia, June 2014.

[18] J. M. Kelif, M. Coupechoux, and P. Godlewski, "A fluid model for performance analysis in cellular networks," *EURASIP J. Wireless Commun. Networking*, Jan. 2010.