Rethinking Energy Efficiency Models of Cellular Networks with Embodied Energy

Iztok Humar, Huazhong University of Science and Technology and University of Ljubljana
Xiaohu Ge and Lin Xiang, Huazhong University of Science and Technology
Minho Jo, Korea University
Min Chen, Seoul National University
Jing Zhang, Huazhong University of Science and Technology

Abstract

The continuous increase in energy consumption by cellular networks requires rethinking their energy efficiency. Current research indicates that one third of operating energy could be saved by reducing the transmission power of base stations. However, this approach requires the introduction of a range of additional equipment containing more embodied energy — consumed by all processes associated with the production of equipment. This problem is addressed first in this article. Furthermore, a new cellular network energy efficiency model with embodied energy is proposed, and optimization between the number of cells and their coverage is investigated. Contrary to previous works, we have found that embodied energy accounts for a significant proportion of total energy consumption and cannot be neglected. The simulation results confirm an important trade-off between operating and embodied energies, which can provide some practical guidelines for designing energy-efficient cellular access networks. The new model considering embodied energy is not limited to just cellular networks, but to other telecommunications, such as wireless local area networks and wired networks.

Over the last two decades, wireless and particularly mobile communications have become increasingly popular with consumers. However, the extensive growth in the number of users, new products and services, and rising service usage times are resulting in increased demand for energy consumption in cellular networks.

Energy Consumption of Cellular Networks in Figures

From an operation point of view, approximately 3 percent or 600 TWh (Terawatt-hour) of the total worldwide electrical energy is consumed by information and communication technology (ICT) [1]. By the end of 2030, this number is expected to grow to 1700 TWh. Herein, the total electric energy consumed by telecommunications equipment is estimated at one third that of information and communications technology's (ICT's), or roughly one percent of the world's total electricity consumption. Representing the strongest branch of the telecommunication sector, mobile telephony is responsible for half of its consumption [2].

Detailed insight into the energy consumed to operate mobile telephony services reveals that only around 10 percent of the entire consumption is associated with the end-user equipment, while the remaining 90 percent is taken up by network components [3], of which around two thirds is used by the base stations (BSs) (Fig. 1).

During the past years, mobile service providers have increasingly recognized the importance of energy-related topics. There are at least two strong motivating factors that drive further research and development in this field. First, it is crucial to minimize the environmental impact of this sector on climate change, caused by increased CO_2 and other greenhouse gases (i.e., methane, nitrous oxide, and ozone) concentration levels in the atmosphere, emitted due to the use of fossil fuels as a primary source for producing electrical energy. Second, aside from their corporate responsibility regarding environmental protection, cellular network providers are also becoming aware of their energy bills, which can take from 18 percent (EU) to 32 percent (India) of their operational expenses (OPEX). Thus, reducing energy consumption in cellular networks will have direct economic effects.

The Problem of Past Research

In previous works, scientists have suggested many approaches to reduce the energy consumption of BSs. In new sectors (e.g., mobile telephony), optimizing operating energy consumption usually precedes optimization including the embodied energy. Besides environmental concerns, the major objective for operators is OPEX reduction. While operating energy consumption has a direct impact on cost, embodied energy only has an indirect one depending on the pricing policy of the manufacturer. Another important reason to start with optimizing operating energy consumption is the risk of making operating energy consumption so high that it becomes difficult to supply all the energy required.

Although many papers have lately been published in the

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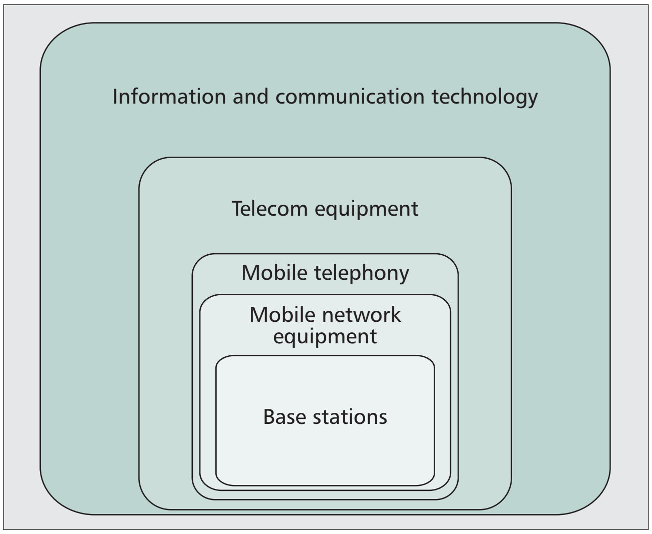

Figure 1. *The proportions of energy consumption of different subsectors.*

field of operating energy optimization, we draw attention to selected cases related to system-level architecture and specific features of cellular networks.

In [4], the optimal energy savings in cellular access networks is addressed, suggesting powering down underutilized BSs during periods of low traffic. To maintain coverage after reducing the number of BSs, the emitted (operating) power of active BSs has to be increased. The authors neglected this increment, avoiding the optimization problem of finding the lowest operating energy with a different number of BSs and their coverage. Using trapezoidal and measured daily traffic patterns, operating energy savings of 25–30 percent has been achieved.

Similarly, the authors in [5] propose cell size optimizations between large and small cell deployments. Upgrading the optimization process between the number of cells and their coverage has been proposed using the power-down strategy by shutting down cells without active users while maintaining the system capacity. Using simulation, they have shown that reduction of cell sizes improves the operating energy consumption ratio (the energy needed to transfer a bit of information).

Another approach is given in [6], suggesting improvements in energy efficiency by employing a two-tier cellular access network. The main idea of two-tier networks is to extend the conventional macro sites with the deployment of microcells covering much smaller areas with cell radii between several meters to several hundred meters. The advantage is not only to provide better coverage for the blind spots in macrocells, but also to provide lower transmission powers while maintaining the same network capacity and saving additional energy by eliminating the considerable effects of wall path losses with indoor cell BS solutions.

The above proposals are all based on optimizing the operating energy consumption required for area coverage and capacity maintenance by improving energy efficiency via increasing the number of deployed BSs with reduced transmission power.

However, there are two notable drawbacks to the above suggestions that require further attention. Even if we disregard the problem that most of today's widely employed BSs do not yet support a sudden total power-down strategy, there is still the issue of embodied energy consumed by manufacturers to produce high-tech equipment such as BSs. Analyses and discussions have not considered the effects of embodied energy, claiming mostly that there are no publicly available data to collect the required parameters [5], or simply ignoring it without providing any reason.

The Need to Rethink the Previous Approaches

To the best of our knowledge, so far none of the available research literature has investigated the issue of energy efficiency of cellular networks including embodied energy. However, many authors have identified it as an important direction for further research. In the introduction of [5], the authors suggest that "both operating and embodied energies need to be considered in the evaluation," but the latter was neglected in further analysis. The same opinion is shared in [1], which discusses the introduction of femtocells as an enhancement to the architecture of cellular networks. Evaluating the environmental effects of this approach, they noted that the "impact of equipment manufacturing should also be taken into account." The topic has recently attracted many research groups (e.g., Mobile VCE's Green Radio Project, Celtic Eureka R&D Project OPERA-Net, Cool Silicon, FP7 IP Energy Aware Radio, and Network Technologies), standardization bodies (e.g., International Telecommmunication Union [ITU] and the Climate Change standardization landscape, and European Telecommunications Standards Institute [ETSI] Environmental Engineering activities) as well as research departments of cellular network equipment manufacturers, who have started to work toward analyzing the environmental impacts associated with the delivery of their product, aiming at environmentally friendly outputs and solutions.

The Importance of Our Results

In this article we propose a new energy efficiency model for BS energy consumption, emphasizing the embodied energy constituent that has not been considered in any previous studies. The simulation results show the important trade-off between operating and embodied BS energy consumption in cellular networks. All of these results provide some guidelines for manufacturers, operators, and researchers.

The remainder of the article is organized as follows. We provide background on embodied and operating energies, followed by a description of a new energy efficiency model. The model is employed in simulation scenarios, and optimizations are given for the operating and embodied energies of a cellular network. Based on the presented results and findings, future challenges for equipment manufacturers, telecommunication providers, and researchers are given, followed by conclusions drawn in the last section.

The New Energy Efficiency Model Proposal

It is obvious that a lot of energy is needed to operate network equipment; however, the energy consumed in manufacturing processes of network equipment has been ignored. The following subsections reveal the need to consider embodied energy in the comprehensive energy usage analysis of a mobile telephony network.

Embodied Energy

Embodied energy, E_{EM}, is the energy consumed by all processes associated with the production of a device. The initial embodied energy E_{EMinit} comprises the energy used to acquire and process raw materials, transport, manufacture components, and assemble and install all products in the initial device construction. Maintenance embodied energy, E_{EMmaint}, includes the energy associated with maintaining, repairing, and replacing materials and components of the device throughout its lifetime.

As noted in our review of past studies above, considering the embodied energy in the process of total energy evaluation in the field of cellular networks has not yet been adequately addressed. However, it has a long tradition in other fields, such as buildings [7], cars [8], photovoltaic panels [9], and

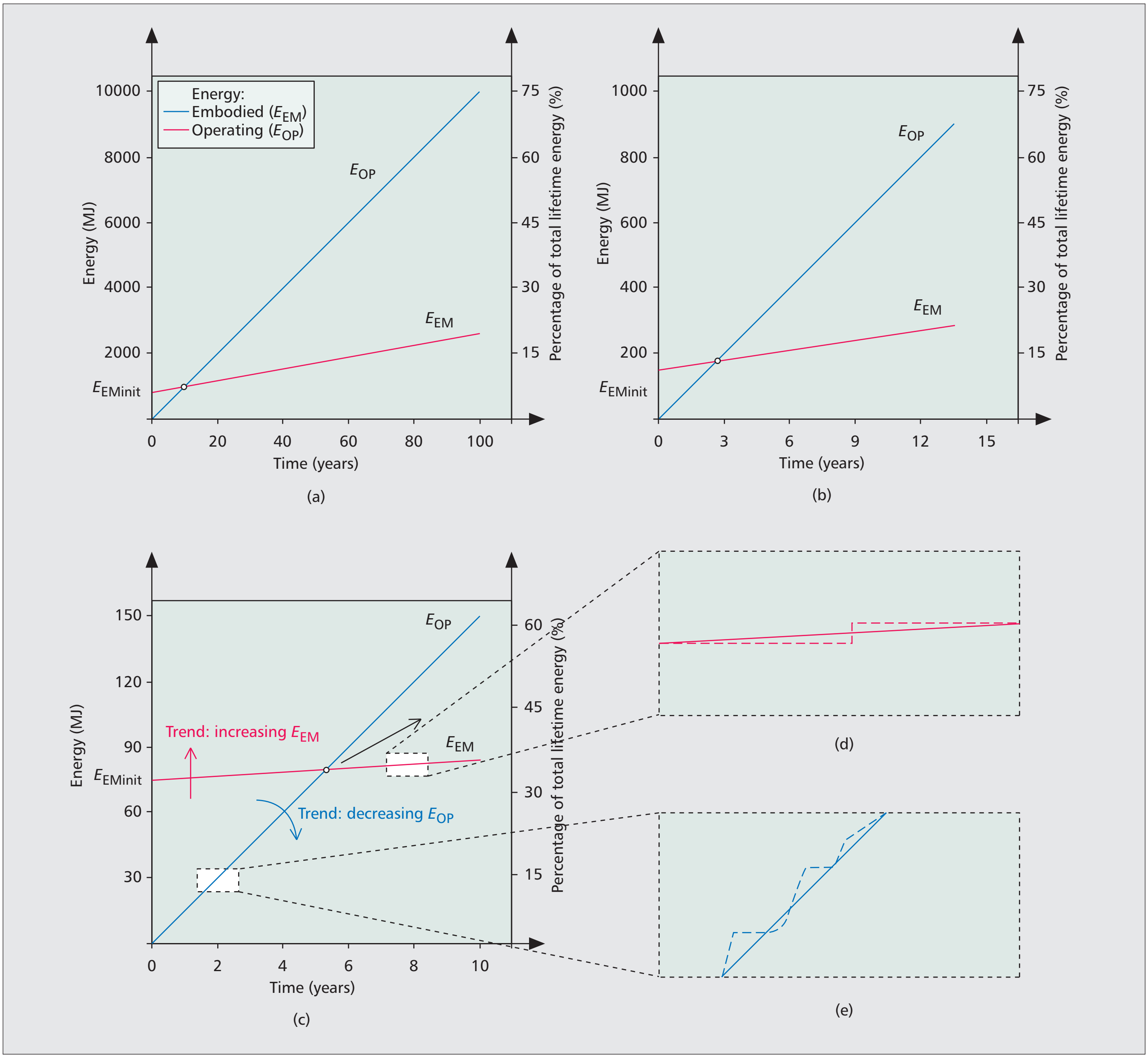

Figure 2. *Embodied and operating energies of a) a house; b) a car; and c) a BS — d) maintenance energy; e) operating energy — during their lifetimes.*

even areas closely related to telecommunications, like computers [10], network switches [11], and mobile phones [12]. Figure 2 shows the relation between the embodied and operating energies for exemplary products of three selected societies (urban, industrial, and information) during their life-cycles: house [7], car [8] and base station. (The results for BSs are based on our research, explained in the next section. These results are provided in advance here to highlight the importance of considering embodied energy in BSs). Although the numbers presented in these figures are rough estimations of averages for considerably varying values (e.g., embodied energy of buildings depends on the traditional construction materials used in different countries, while their operating energy depends on climate conditions) [7], an obvious difference among them leads to the following conclusions.

The shift of the intersection point between the curves of embodied and operating energies in the upper right position demonstrates that the ratio between embodied and operating energies during the life cycle of modern electronic equipment (e.g., BSs) is much higher than that for the house or car. This is due to the sophisticated and energy-intensive production of semiconductors, minimized operating energy consumption of these devices, and their relatively short life cycles due to frequent replacements caused by advancing technology.

The scale on the right side explains the share (percentage) of the initial embodied energy relative to the total energy used in a product's total lifetime. The embodied energy represents a relatively small part of the total energy in the case of houses (7–10 percent) or cars (10–15 percent) compared to electronic devices such as BSs (30–40 percent). It is surprising that the problem of embodied energy is studied in depth in the aforementioned disciplines, while research work in the area of cellular networks simply neglects it.

Embodied Energy Assessment of a General BS

Several different methodologies exist to assess initial embodied energy of a device, ranging from the well-known life cycle assessment (LCA), employing very extensive study, requiring

Material/process	Energy requirement	Value	Energy	Source
	MJ/kg		GJ	
Materials				
Semiconductor devices (silicon wafers, integrated circuitry)	60,000–120,000	.31	37.2	Analytical/literature
Metals (aluminum, cooper, steel, lead, zinc)	100–400	20.0	7.0	Analytical/literature
Bulk materials (plastic, glass, rubber)	20–400	14.0	5.8	Analytical/literature
Printed circuit board (incl. manufacturing and assembly)	300–500	8.6	4.3	Analytical/literature
Telecom cables, installations	50		2.3	Estimated
Manufacturing processes, transportation				
Components manufacturing and node assembly			8.1	Estimated
Supply chain			5.3	Estimated
Transportation, setup			3.5	Estimated
Conventional manufacturing (cutting, welding, machining finish, injection moulding)			1.5	Estimated
Total embodied energy of a base station			**75.0**	

Table 1. *The constituents of the initial embodied energy for materials and processes during the production of a general BS.*

data that are not easily available and taking a great deal of time to be completed, to the ecological footprint analysis (EFA) and key environmental performance indicators (KEPI) approach, which is easier to use, and requires less time and input data. Although some manufacturers [12] have already conducted at least some parts of an LCA, the collected data is usually kept confidential or provided after a great delay. Alternatively, the data is provided merely in an aggregated form [2] (e.g., for the entire equipment of a mobile operator's network in a single assessment), which makes it impossible to distinguish the embodied energy of a single BS. Most publicly available data is given for commercial purposes, which makes them questionable in terms of reliability and accuracy, and therefore not applicable to further studies. Consequently, a new and different approach [13] that enables an external observer to estimate the initial embodied energy of a general BS is required.

Methodology — Our approach uses similar methodology to that of a recently published work [11]: disassembling of a BS and building the lifecycle inventory for the most notable components, materials, and processes for a general BS (summarized by categories in Table 1). The estimations of embodied energies for individual categories were made on a per-mass basis, according to energy contents for different materials and manufacturing processes, available in databases and studies (i.e., Ecoinvent database, Energy using Products studies, [10, 13] and references therein). The total initial embodied energy of the general BS has been assessed by summing the results provided in Table 1.

As for the constituent materials, a BS contains a large variety of materials and substances, making up several thousands of components. The core of the BS is a set of printed wiring boards with active electronic components, such as integrated circuits (mostly composed of semiconductor materials), and passive electronic components, such as resistors, capacitors, conductors, and connectors. The passive electronic components usually account for only 1 percent of the total initial embodied energy [12]. However, from the constituents of the initial embodied energy of a general BS, provided in Table 1, it is evident that the majority of a state-of-the-art electronic device's embodied energy is used for semiconductor processing and manufacturing. This is due to the very complex processes of wafer manufacturing that may include up to several hundred distinct process steps. The share of energy used for semiconductor devices in our estimation is in agreement with the results found in [13], revealing that in the computer industry, almost 95 percent of the energy content for electronics manufacturing goes into wafer manufacturing/chip packaging. As the BS site consists of not only the BS's equipment but also antenna towers, transmission equipment, power equipment, climate (cooling) equipment, and housing, the share of embodied energy of semiconductors in a general BS is not expected to be as high as that of computers. The embodied energy for the remainder of material constituents is summarized in the following groups: bulk and metal materials, and telecommunication cables. They are based on the breakdown of materials from the data collected about real macrocell BSs, evaluated using the sources given above.

The energy of the following processes has been estimated based on discussions with manufacturer providers: components manufacturing and node assembly, conventional manufacturing, supply chain, transportation, and setup and installation of a BS.

To verify our results, we have compared the estimated energy of the BS with a powerful state-of-the-art computer server. As expected, the embodied energy of the BS exceeds the embodied energy of the computer server, but the results are on the same order of magnitude. A similar observation can be noted when comparing the embodied energy of BS with the embodied energy of a network (aggregation) switch [11]. Our results are also in accordance with [2], claiming that approximately 20 percent of mobile devices' lifetime energy is used by raw materials.

Uncertainty and Caveats — The results of embodied energy estimation go along with certain uncertainties, which are summarized into two categories:

- Uncertainties in the data for material production or processes considered in our analysis
- Uncertainties in the estimation of material amounts and processes, varying at different BS equipment manufacturers

A great discussion on this topic is provided in [10], stating that variations in data for bulk materials and semiconductor production can be assumed to be ±30 percent, printed circuit boards ±21 percent, and assembly ±79 percent. As the energy required for semiconductors contributes the majority to estimated embodied energy, its error value can be used as a reference. On the other hand, the compounds of macrocell BSs produced by different manufacturers can significantly vary according to the type of materials and components used, also evident through different total weights of BS equipment. This uncertainty is estimated with ±40 percent tolerance. As these errors are presumably uncorrelated, they add in quadrature in the total result as high as ±70 percent.

Furthermore, the embodied energy content of the BS varies greatly according to different construction types. Our study is hereafter focused on the macrocell BS only, albeit the equipment manufacturers provide heterogeneous assortment of femto/pico/microcell BSs with varying power, dimensions, and embodied energy. However, a lower output radiation power of a BS usually does not guarantee lower embodied energy of the equipment; just the opposite, higher integration and complexity of contemporary small-cell BSs and their shorter lifetimes increase the share of embodied energy in total lifetime energy compared to macrocell BSs.

It should also be noted that our approach focuses strictly on materials and manufacturing processes. As a consequence, some parameters, such as research and engineering activities, software development, and end of product life impacts (which are also energy consuming) were disregarded, since they are difficult to relate to specific processes or products. This is also an interesting direction for further research in the field of total life cycle assessment that has to be carried out in cooperation with equipment manufacturers and requires separate attention.

Maintenance Embodied Energy

The maintenance embodied energy is associated with maintaining, repairing, and replacing materials and components of the BS throughout its lifetime. In Fig. 2d the red dashed line shows that maintenance activities are performed consecutively at certain time increments, which can be interpreted as a linear function of time, illustrated with the red solid line in the same graph. The estimations of maintenance embodied energy are based on the numbers provided by mobile operators. They differ with a BS's location [4], but in general, it can be modeled by 1 percent of the initial embodied energy per year [19].

Importance of Lifetime

To be able to compare the manufacturing phase with the operation phase of the BS throughout its life cycle, the lifetime of the studied products must be reflected in the model. In our study, the lifetime of a BS has been estimated as T_{lifetime} = 10 years [2]. However, this estimation corresponds to the anticipated commercial lifetime, which in many cases is substantially shorter than the technical lifetime. Since new technologies emerge very fast, the equipment is usually replaced before the end of its lifetime, which extends the share of embodied energy in the BS's total lifetime energy. This high-energy intensity of manufacturing, combined with short equipment turnover times further encourages the need to rethink the suggested energy efficiency models.

Operating Energy

The BSs in the worlds' cellular communication networks consume approximately 60 TWh/year. The analysis in [15] has further decomposed this energy into the effects of power amplifier, idling transceiver, power supply, cooling fan (its portion can vary with different climate conditions), transceiver power conversion, combining/duplexing, central equipment, transmit power, and cabling (Fig. 3).

For a typical macrocell installation (for simplicity, this study evaluates a macrocell architecture only; the employment of smaller (femto/pico/micro) cells in a multi-tier architecture is subject of further research), the net power of a BS can vary from 0.4 kW – 3.0 kW. In [3], the authors have estimated the average power consumption of equipment dating before the year 2000 as 1.1 kW. From this time forward, the power consumption of the BSs is claimed to be reduced to less than 500 W [20]. Thus, for further modeling we will presume this number as an average power consumption of a state-of-the-art BS. As the radio access in a cellular network is intended to work continuously, the annual operating energy consumption is estimated at roughly 15 GJ, resulting in 150 GJ in the estimated device's lifetime.

Moreover, the power consumption of a single BS depends on traffic load, and it spreads statistically. As represented in Fig. 2e with the blue-dashed line, the power consumption is a non-linear function of time, with some high-consumptive busy periods as well as periods with no power consumption, representing the possible power-down intervals during low traffic. The average value used in our study can be represented as a linear function of time, illustrated with the blue-solid line.

For further simulation process, it should be noted that the operating energy E_{OP} can be further divided into two parts: E_{OPlin}, which is linearly scaled with the transmission energy, representing the power amplifier and feeder losses, cooling, etc. [6], and a constant part E_{OPconst}, representing the fixed energy consumed by signal processing, battery backup, etc. ($E_{\text{OP}} = E_{\text{OPlin}} + E_{\text{OPconst}}$). Consequently, the linear relation of BS's operating power (P_{OP}) to its transmission power (P_{TX}) can be applied for further calculations: $P_{\text{OP}} = a \cdot P_{\text{TX}} + b$.

Total Energy Consumption Model

With regard to the conclusions given in the previous sections, the total energy consumption model of a single BS includes both embodied and operating energies, i.e., $E = E_{\text{EM}} + E_{\text{OP}} = (E_{\text{EMinit}} + E_{\text{EMmaint}}) + (E_{\text{OPlin}} + E_{\text{OPconst}})$. The initial embodied energy (E_{EMinit}) is expended once in the initial production of the BS, while maintenance embodied (E_{EMmaint}) and operating energies accrue over the effective lifetime of the BS, and can be expressed as $E_{\text{EMmaint}} = P_{\text{EMmaint}} \cdot T_{\text{lifetime}}$, $E_{\text{OP}} = P_{\text{OP}} \cdot T_{\text{lifetime}}$, respectively (A nomenclature providing the variables is given in Table 2).

The ratio between embodied and operating energies during the BS's lifecycle is evident in Fig. 3. The results of our estimation are confirmed by the aggregated data given by [2], where the authors found that the share of the embodied energy in the aggregated cellular network's total energy was approximately 25 percent in 2005 and had grown to 43 percent by the end of 2006. It also confirms our claim that operating energy is being reduced on behalf of increased embodied energy.

Sleep-mode or power-down strategies, suggested in available works [4–6], will further decrease the operating energy compared to that of embodied energy.

Energy Efficiency Model

The energy efficiency can be evaluated through the energy consumption ratio (ECR) [21] between a system's energy consumption and its capacity (Joules per bit). Obviously, the relation to energy efficiency is reciprocal: when ECR is high, energy efficiency is low, and vice versa. In our energy efficiency model embodied energy is also considered, extending the ratio to ECR = $E_{\text{system}}/C_{\text{system}}$, where E_{system} represents the total energy consumption of a cellular network system, and C_{system} represents the system capacity.

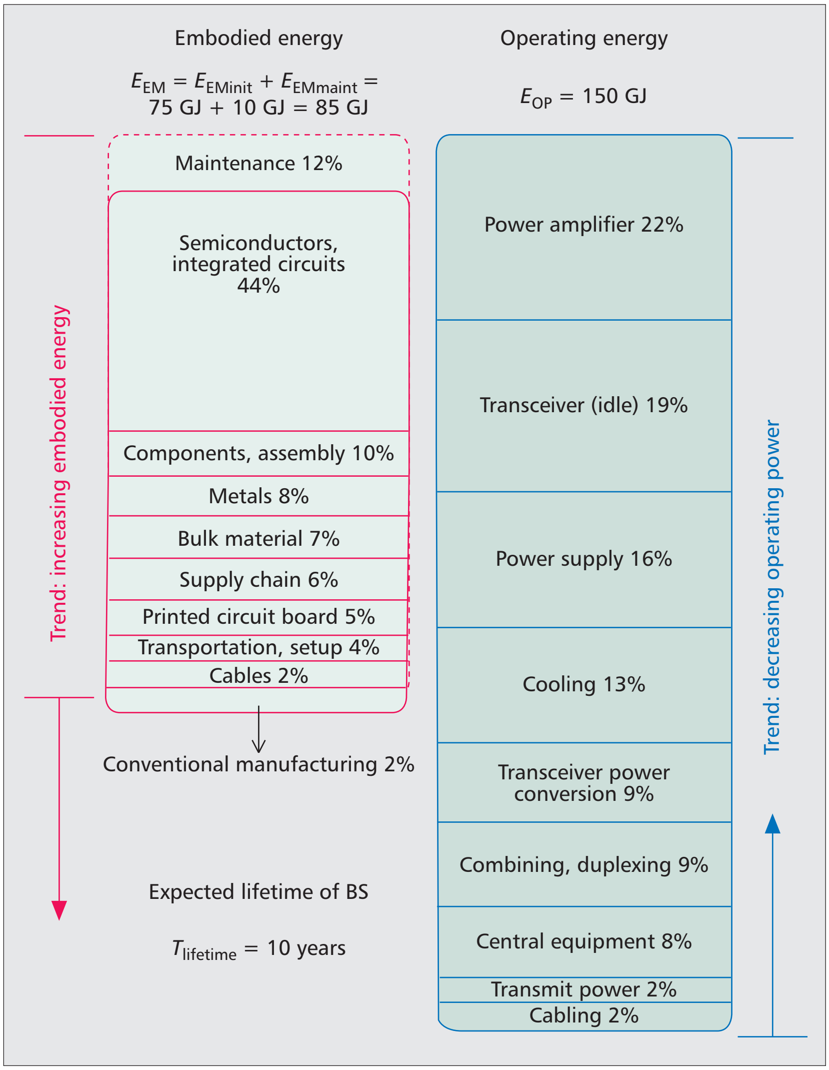

Figure 3. *The proportion of embodied and operating energy during a BS's lifetime: breakdowns and trends.*

The Cell Number/Coverage Trade-Off

In this section we apply our energy consumption model to two scenarios, excluding and including the power-down strategy. A simple simulation has been conducted to provide energy consumption optimization with respect to the number of cells and their coverage, considering the trade-off between operating and embodied energy. The results are as follows.

The Energy Consumption Model without the Power-Down Strategy

The transmission power of BS antennas is dissipated into the air, and the transmitted signal is deteriorated by path loss, shadowing, and multipath fading effects in wireless propagation channels. The average receiving power decreases with distance d between the receiver and transmitter approximately $1/(d)^{\gamma}$, mainly accounting for the path losses, where γ is the path loss exponent that typically ranges from 2 to 5, depending on the propagation environment. Besides, all the mobile devices within the cell require a certain level of received signal-to-noise ratio (SNR), asserting at least minimum receiving power $P_{\min}$ for acceptable performance. Therefore, the transmission power of the BS P_{TX} is proportional to $P_{\min} \cdot (r)^{\gamma}$, where r represents the cell radius. Considering the link budget for noise, shadowing, and other loss effects (as well as gains), the transmission power can be further scaled with the term $P_{\min} \cdot (r)^{\gamma}$. For simplification, suppose a BS with radius r_0 = 1 km, with transmission power P_0 = 40 W; then the transmission power for BSs with different cell radius can be expressed as $P_{TX} = P_0 \cdot (r/r_0)^{\gamma}$. Referring to the previous section, the operating power $P_{OP} = a \cdot P_0 \cdot (r/r_0)^{\gamma} + b$; and the energy model for the whole system consumption, E_{system}, for the scenario without power-down strategy of a certain area covered by n BSs can be expressed as

$$\begin{aligned} E_{\text{system}} &= n \cdot (E_{EM} + E_{OP}) \\ &= n \cdot (E_{EMinit} + E_{EMmaint} + P_{OP} \cdot T_{\text{lifetime}}) \qquad (1) \end{aligned}$$

where the operating power P_{OP} is a function of cell radius as described above.

The Number/Coverage Trade-Off

The deployment of a larger number of BSs with smaller size (cell radius), such as femto/pico/microcells, will enable the reduction of transmit power of BSs as well as operating power and electromagnetic radiation. However, the total energy consumption of the system is the multiplication of the number of BSs and a single BS energy consumption. As the number of BSs becomes large, the system consumption rises, since the embodied energy of a newly deployed BS adds to the total energy. There is a trade-off between the number and coverage of a single BS, translating into a trade-off between the embodied energy and operating energy. In practical deployments, the position of the BS, the capacity and the traffic requirements are always taken into account. However, to explore the number/coverage problem on a simple scenario, we assume the total coverage to be the multiplication of the number of active BSs and a single BS coverage. Under this coverage constraint, the optimal energy consumption is explored in simulation by considering the trade-off between operating and embodied energy consumptions.

The Energy Consumption Model with the Power-Down Strategy

The power-down strategy is an important energy saving technique adapting BS activities to traffic dynamics. When the traffic of a certain cell remains at a low level, the BS can be shut down for operating energy savings purposes. The other active BSs should increase their transmission ranges by

Abbreviation	Explanation
E_{EM}	Embodied energy
E_{EMinit}	Initial embodied energy
E_{EMmaint}	Maintenance embodied energy
E_{OP}	Operating energy
E_{OPlin}	Part of E_{OP}, linearly scaled with the transmission energy
E_{OPconst}	Part of E_{OP}, not scaled with the transmission energy
E, E_{sytem}	Total energy consumption
P_{min}	Minimum receiving power for acceptable performance
P_{OP}	Operating power
P_{TX}	Transmission power
C_{system}	System capacity
γ	Path loss exponent
T_{lifetime}	(Commercial) lifetime of base station
T_{active}	Active time during (commercial) lifetime

Table 2. *Nomenclature providing the variables.*

increasing the transmission power to cover the entire area. When the traffic in a cell increases, the shutdown BS will be activated. Thus, when the power-down strategy is applied, the operating power of the system varies with the number of active BSs. The average traffic intensity in a day or year varies periodically between its peaks, sometimes assumed to have a trapezoidal or sinusoidal pattern [4]. Consider the uniform distribution of users in the cells and the random use of mobile devices; the traffic patterns among different BSs are the same except that the traffic peaks are uniformly distributed during the period. Each BS in an area has a power-down probability p proportional to the share of the low traffic period in the day. At a particular time, there may be M powered-down BSs, where M is a random variable satisfying binomial distribution: Prob $(M = m) = \binom{m}{n} p^m (1-p)^{n-m}/(1-p^n)$, $0 \leq m \leq n-1$, and n again is the total number of BSs covering the area. The energy model for the entire system consumption E_{system} for the scenario with power-down strategy is expressed as follows:

$$E_{\text{system}} = n\cdot(E_{\text{EMinit}}+E_{\text{EMmaint}}) + \sum_{m=0}^{n-1}(n-m)\cdot \text{Prob}(M=m)\cdot P_{\text{OP}}(n-m)\cdot T_{\text{active}} \qquad (2)$$

where, as distinguished from Eq. 2, the operating energy consumption is the probabilistic average over the distribution of random variable M; and the active time T_{active} of BSs can be estimated by $(1-p)\cdot T_{\text{lifetime}}$.

When considering the power-down strategy, the operating power of BSs can be reduced by around 25 percent [1, 4]. The operating energy savings are significant, especially when more BSs are deployed. However, our study argues that the embodied energy consumption will be more proportional to the total energy consumption than in the case without the power-down strategy. Reconsidering the number/coverage problem, if a large number of smaller BSs are deployed, the embodied energy consumption increase will be dominant in the total energy consumption. This means that the BS is manufactured at great energy cost, while it is powered down during most of its lifetime. Therefore, considering the power-down strategy is most necessary for the number/coverage trade-off problem resolution.

Simulation Results

In this section the presented energy consumption models are evaluated in simple simulation scenarios in order to optimize the total energy consumption by exploring the trade-off between operating energy and embodied energy. Consider a typical urban area of radius $R = 5$ km covered by n BSs with the same cell radius r as illustrated in Fig. 4, demonstrating the deployment of BSs with two different cell radii r_1 (Fig. 4a) and r_2 (Fig. 4b), where $r_1 > r_2$. During the simulation, the embodied energy is calculated using the estimated data presented earlier. The path loss exponent is set as $\gamma = 3.2$ in a typical urban environment to evaluate the operating energy. The power-down probability is set to $p = 1/4$ for the energy consumption model with the power-down strategy. As for the operating power consumption model, the parameters are set as $a = 7.84$ and $b = 71.50$ W according to [6], while the data provided earlier is applied for the embodied energy model.

Under this simulation scenario, the energy consumptions with a different number of BSs or cell sizes are evaluated in Matlab, both including and excluding the power-down strategy, to find the optimal number of BSs or cell size, as depicted in Fig. 5. It is evident that an optimal number of BSs or cell size with minimal energy consumption exists. When only a small number of BSs with large cell sizes are deployed, the energy consumption is high; this is due to the increased operating energy with cell size. However, when a large number of BSs with small cell sizes are deployed, the embodied energy consumption dominates and leads to an increase in total energy consumption. The optimum is achieved with the trade-off between operating energy and embodied energy. Compared to [16], where the optimal cell size/number of BSs is affected only by the fixed operating energy consumption part, the embodied energy in our case has much stronger effects when the cell size becomes small or the number of BSs becomes large. This finding averts from the suggestions that energy savings can be achieved with a larger number of cells with reduced transmission power. Besides, when the power-down strategy is applied, the operating energy savings will only slightly shift the optimum to a higher number of cells due to the decreased operating energy consumption. However, in practical deployments the power-down strategy is only possible when the number of BSs is relatively large. This emphasizes the problem of embodied energy and even raises its share in the total energy when the power-down strategy is applied.

The results of energy efficiency vs. the number of BSs are provided in Fig. 6. Since the system capacity increases linearly with the number of active BSs [5], ECR will decrease by increasing the number of BSs. The results, ignoring the embodied energy, are in accordance with the previous research [5]. However, the energy efficiency of both models, with or without considering the embodied energy, are almost the same when the number of cells is small; however, considering the embodied energy reveals that several times more energy is required for the same capacity when the number of cells is large (detailed on the scaled part of Fig. 6). This again calls for reconsidering past suggestions on energy saving solutions.

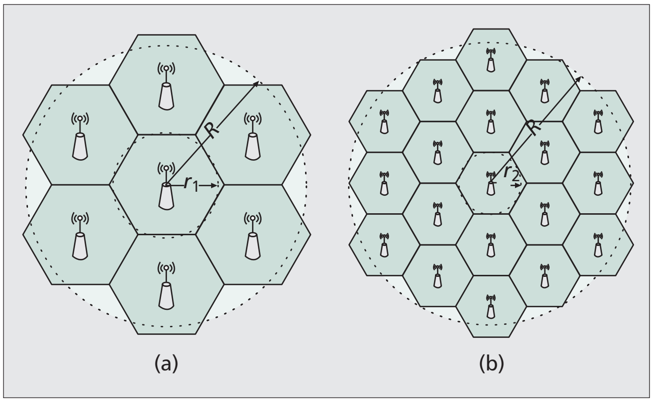

Figure 4. *The simulation scenario topologies: a) large cell size (r_1); b) small cell size (r_2).*

Future Challenges

The above results and findings give insight into the BS energy model, and propose optimizations of the number of BSs and cell coverage considering embodied and operating energies. However, there remain many questions that manufacturers, operators, and researchers must address in future work.

Equipment manufacturers should advocate total life cycle assessments, including the energy consuming activities of research, engineering, software development, and end of product life impacts. Cooperating closely with component suppliers, equipment manufacturers should perform cradle-to-grave assessments of embodied energy for at least a selected set of their radio network product portfolio. This will be of great interest to operators and researchers in relation to network optimization and analysis, respectively. Furthermore, the up-to-date embodied energy estimations should be made publicly available, and simple to interpret and use, even for non-experts in the field of LCA.

Moreover, manufacturers should strengthen the awareness of embodied energy and the environmental impacts of non-mass produced equipment such as BSs, as they do for mobile phones [12]. Manufacturers should inform the customers not only about the improvements in operating energy consumption but also the assessed embodied energy of the equipment should be provided. To ensure this outcome, the standards of embodied energy measurement and estimation should be made a matter of regulation and enforcement by the regulatory authorities.

Operators should perform a cost analysis for building new BS sites in terms of energy, expenditure, and environmental impacts. Considering the different characteristics of macro, micro, pico, and femtocells, the issue of optimizing the energy efficiency model with embodied and operating energies for two-tier cellular networks is still an open research problem. In addition, the impact of different application contexts, such as online movies, interactive games, and reading online news, as well as related quality of service provisioning [17] on the energy efficiency of cellular networks should also be addressed.

Although there exist some obstacles for public and creditable embodied energy data, this is not an excuse to neglect its influence on energy efficiency modeling and optimizations. We hope our work provides further motivation in this perspective, although there remain many open research issues such as the design and deployment of two tier architecture, BS position optimizations, and analyses in real network conditions. Based on our energy model proposal, the impact of further identified conditions, such as wireless network traffic, transmission rates, and signal-to-interference-plus-noise ratio (SINR), on energy efficiency should be further investigated.

There is also some evidence that operating energy is being reduced on behalf of increased embodied energy. To explore the relationship between the embodied and operating energies is an interesting question for further research.

Although this article mainly focuses on cellular networks as they have attracted much attention in recent ongoing research, the results of our study are general and can easily be applied to other fields of telecommunications. For instance, the proposed models are directly applicable to wireless local area networks. The provided approach of embodied energy consideration may also target other energy efficiency concepts, requiring the deployment of additional hardware to save energy. The network connectivity proxying scheme [18], for example, employs external network proxies that virtually maintain presence for network computers but let them powered-down and save energy while idle. This approach may require additional hardware and should be further evaluated by considering the embodied energy limitations.

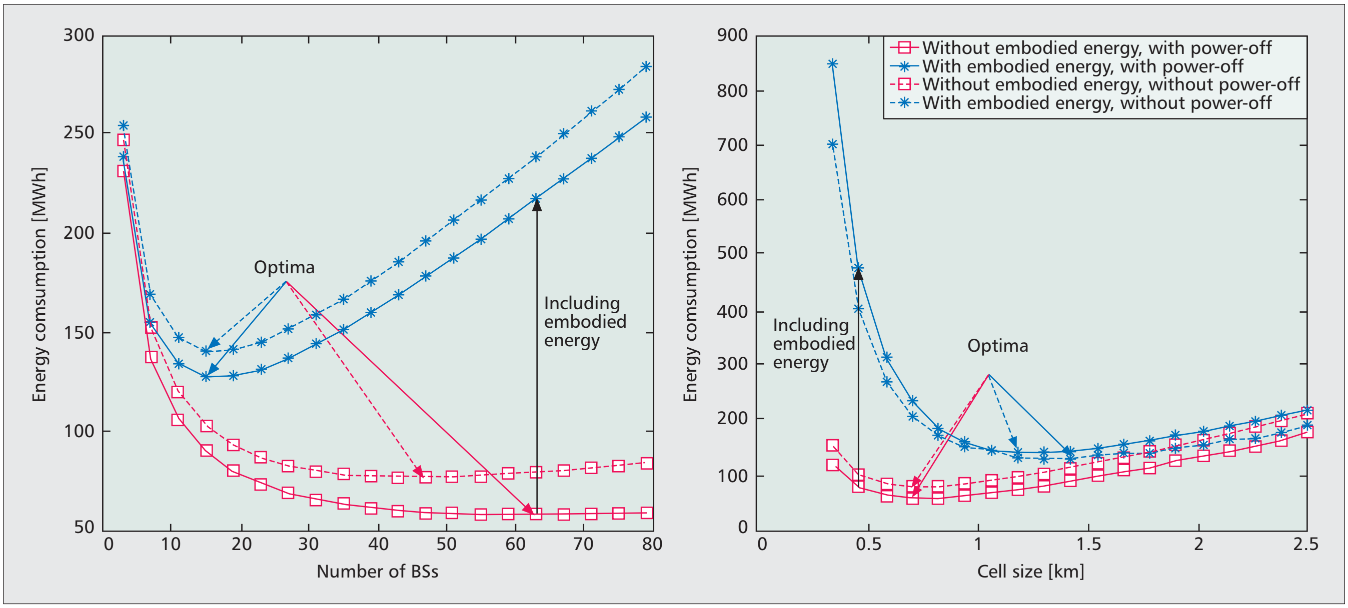

Figure 5. *The optimal energy consumption of a cellular network with respect to the number of BSs or cell sizes.*

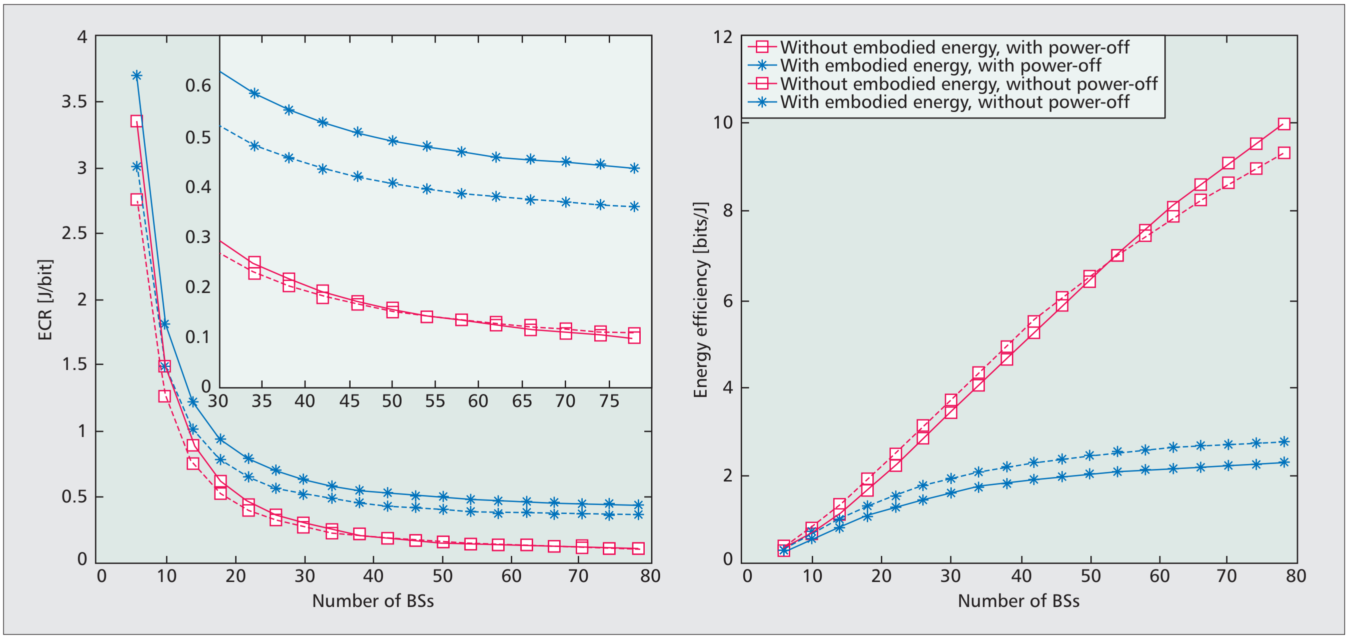

Figure 6. *ECR and energy efficiency of a cellular network, covering the same area with a different number of BSs.*

Conclusion

Until recently, major energy saving endeavors have been focused on reducing the operating energy of a cellular network, ignoring the embodied energy. However, our research reveals that the embodied energy accounts for a significant proportion of the energy consumed by a BS over its lifetime. Compared with traditional research in this field, our results show that the telecommunications industry should face up to the challenges of rethinking the energy efficiency of cellular networks across-the-board. Based on the proposed energy efficiency model and simulation results, our findings tend to disagree with suggestions to use an increased number of BSs with lower transmission power and power-down strategy to perform energy savings.

Moreover, further solutions of energy efficiency optimization should consider a trade-off between the embodied and operating energies in cellular networks, as suggested by our work. However, to fully estimate and improve the energy efficiency of cellular networks, researchers, manufacturers, operators, and regulatory authorities should work together to establish a framework of energy efficiency covering all telecommunication stages, which include the concept definition, life cycle assessments, standards regulation, expense estimation, and so on. If this is done, a veritable challenge would indeed emerge, in the next round of the telecommunications revolution.

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Biographies

IZTOK HUMAR [M'01, SM'10] (iztok.humar@fe.uni-lj.si) received Ph.D. degrees in telecommunications from the Faculty of Electrical Engineering (FE) and information management at the Faculty of Economics, University of Ljubljana, Slovenia, in 2007 and 2009, respectively. He is an assistant professor at the FE, where he lecturers on design, management and modeling of telecommunication networks. His main research topics include the design, planning and management of telecommunications networks and services, as well as measurement and modeling of network loads and traffic. Currently, he is a visiting professor at Huazhong University of Science and Technology (HUST), China, where he works on energy-efficient wireless networks. Currently, he serves as IEEE Communication Society of Slovenia Chapter Chair, MMTC member, and IEEE Slovenia Section Secretary.

XIAOHU GE [M'09] (xhge@mail.hust.edu.cn) is currently a full professor with the Department of Electronics and Information Engineering at HUST. He received his Ph.D. degree in communication and information engineering from HUST in 2003. He has worked at HUST since 2005. Prior to that, he worked as an assistant researcher at Ajou University, Korea, and Politecnico Di Torino, Italy. He has been invited to work as the project review expert by NSFC and MOST in China. He is a Senior Member of the China Institute of Electronics and China Institute of Communications. His research interests are in the area of mobile communication, traffic modeling in wireless networks, as well as interference modeling in wireless communications.

LIN XIANG received his Bachelor's degree in electronic and information engineering from HUST in June 2009. He is currently working toward his Master's degree in communication and information systems at HUST. His present research direction is traffic modeling in wireless networks and green wireless networks.

MINHO JO [M'07] (minhojo@korea.ac.kr) received his Ph.D. degree from the Department of Industrial and Systems Engineering, Lehigh University, Pennsylvania, in 1994. He was a staff researcher with Samsung Electronics. He is currently a Brain Korea Professor at Korea University, Seoul. He is Founder, Editor-in-Chief, and Chair of the Steering Committee of *KSII Transactions on Internet and Information Systems*, an Editor of *IEEE Network* and the *Journal of Wireless Communications and Mobile Computing*, and an Associate Editor of the *Journal of Security and Communication Networks* (Wiley). He is Executive Director of tje Institute of Electronics Engineers of Korea and the Korean Society for Internet Information, respectively. His research interests include cognitive radio, network security, wireless communications, mobile computing, and radio-frequency identification.

MIN CHEN [M'08, SM'09] is an assistant professor in the School of Computer Science and Engineering at Seoul National University. He received the Best Paper Runner-Up Award from QShine 2008. He is TPC co-chair for BodyNets 2010. He is managing editor of *International Journal of Autonomous and Adaptive Communications Systems*. He serves on the editorial boards of several journals, such as *WCMC*, *IET Communications*, Wiley *SCN*, *JIT*, and *IJSNET*.

JING ZHANG is currently an assistant professor in the Department of Electronics and Information Engineering at HUST. He received his Ph.D. degree from the Department of Electronics and Information Engineering at HUST in 2010. His research interests are in the areas of mobile communication, green communication, and interference modeling in wireless communications.