Energy Harvesting Small Cell Networks: Feasibility, Deployment and Operation

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Abstract

Small cell networks (SCNs) have attracted great attention in recent years due to their potential to meet the exponential growth of mobile data traffic and the increasing demand for better quality of service and user experience in mobile applications. Nevertheless, a wide deployment of SCNs has not happened yet because of the complexity in the network planning and optimization, as well as the high expenditure involved in deployment and operation. In particular, it is difficult to provide grid power supply to all the small cell base stations (SCBSs) in a cost effective way. Moreover, a dense deployment of SCBSs, which is needed to meet the capacity and coverage of the next generation wireless networks, will increase operators' electricity bills and lead to significant carbon emission. Thus, it is crucial to exploit off-grid and green energy sources to power SCNs, for which energy harvesting (EH) technology is a viable solution. In this article, we will conduct a comprehensive study of EH-SCNs, and investigate important aspects, including the feasibility analysis, network deployment, and network operation issues. The advantages, as well as unique challenges, of EH-SCNs will be highlighted, together with potential solutions and effective design methodologies.

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I. INTRODUCTION

The proliferation of mobile devices, such as smart phones and tablets, is boosting the data traffic explosion in wireless ecosystems. In this context, cellular networks are faced with the challenges of providing enormous network capacity, achieving superior cellular coverage, and improving users' quality of experience. The small cell network (SCN) is a cost-effective and energy-efficient network paradigm to tackle these challenges. In SCNs, the densely-deployed small cell base stations (SCBSs), including micro, pico, and femto-cells, bring the spatial reuse of radio resources to a new level, which will then help improve the area spectral efficiency and user experience. Besides this, the low-cost and low-power SCBSs can be easily installed without costly cell site acquisition, and their self-organization manner further helps save operating expenditures [1, 2].

However, as the SCBSs are densely and irregularly located, some of them may be inaccessible to the power grid. Moreover, the network power consumption of the SCNs will be high despite the small power consumption of a single SCBS, which will produce a significant amount of carbon emissions. As a result, it is desirable to exploit off-grid and green energy sources to power the SCNs. Energy harvesting (EH) technology is a viable and promising solution, which can harvest ambient renewable energy, e.g., solar and wind energy, to power SCBSs [3]. It is estimated that applying EH techniques to SCNs can achieve a $20\% CO_2$ reduction in the information and communication technology (ICT) industry [4].

Communication networks with EH capability have been extensively studied in recent years, from point-to-point systems [5, 6], to multi-user systems [7] and EH heterogeneous networks [8]. However, so far, there has been no systematic study on how to effectively utilize the EH techniques in SCNs, i.e., how to power the SCBSs by EH, how to deploy EH-SCBSs, and how to optimize the network operations for EH-SCNs. The goal of this article is to provide a comprehensive study for EH-SCNs. Specifically, the feasibility analysis of EH-SCNs will be conducted first, and then the network deployment issues will be addressed from the basic tradeoffs to practical deployment considerations. Over the deployed EH-SCNs, the challenges and design methodologies for network operation will be elaborated.

II. POWERING SMALL CELL NETWORKS BY ENERGY HARVESTING - A FEASIBILITY ANALYSIS

In this section, we will investigate the feasibility of powering SCNs by renewable energy sources. We will first highlight the main differences between the energy consumption models

for the macro base station (BS) and SCBSs, following which the potential of different EH techniques to power SCBSs will be discussed. In particular, it will be revealed that the hybrid solar-wind energy harvester will be an ideal candidate to enable EH-SCNs.

A. The Feasibility of EH-SCNs

The energy consumption models of SCBSs are fundamentally different from the macro BS, which are specified as follows:

- The communication distances from the SCBSs to mobile users will be significantly reduced compared to macro BSs, as SCBSs will be densely deployed [2]. Consequently, the transmit power of SCBSs will be greatly reduced. For example, the maximum transmit power of a typical femto BS is 17 dBm, compared to 43 dBm for a macro BS [9].
- The baseband processing in SCBSs is much simpler than in the macro BS, since several key operations are eliminated, such as the digital pre-distortion.
- Cooling in the macro BS accounts for around 10% of the total BS power consumption [9], while SCBSs can be cooled by natural air circulation.

Given the above discussion, the power consumption of an SCBS is orders of magnitude smaller than the typical macro BS. Specifically, the power consumption of a typical macro BS is 225 W per transceiver. In contrast, it is 72.3 W/7.3 W/5.2 W for a micro/pico/femto BS [9]. Thus, it will be more feasible to power SCBSs by EH. On the other hand, as SCBSs need to be densely deployed, their total energy consumption may still be high. Thus, powering SCBSs by renewable energy sources is also motivated by environmental concern.

To check the feasibility of powering SCNs via energy harvesting, we summarize the main energy sources of EH techniques in Table I. We see that most of the existing applications of EH techniques are limited to low-power electronic devices, mainly due to the low EH rates. Considering the typical power consumption of an SCBS (>5W), only a few of the EH sources are applicable, among which solar and wind energy are the two most promising ones due to the following reasons:

Sufficient harvested energy can be guaranteed with either a solar or wind energy harvester. For example, 100 W electric power can be generated by either a 121 cm × 53.6 cm solar panel under rated sunlight radiation, or by a rotor with a 1 m diameter under an 8 m/s wind speed.

TABLE I: Existing Energy Harvesting Techniques

Energy Sources	Characteristics	Implementation Techniques	Amount of Harvested Energy	Typical Applications
Solar [10]	Uncontrollable,	Photovoltaic cells	15 mW/cm^2	Wireless sensor,
	predictable			household appliances
Wind [10]	Uncontrollable,	Anemometer	85 W (rotor diameter	Wireless sensor,
	predictable		1m, wind speed 8m/s)	household appliances
Environmental	Uncontrollable,	Electromagnetic induction	$0.2~\mathrm{mW/cm^2}$	Wireless sensor,
Vibration [10]	unpredictable			consumer electronic
Human Motion [10]	Controllable,	Piezoelectric	Finger motion: 2.1 mW	On-body monitoring,
	predictable		footfalls: 5 W	portable devices
Thermal [11]	Uncontrollable,	Thermopiles	$pprox 40~\mathrm{mW}$	Wireless sensor
	unpredictable			
Ambient	Uncontrollable,	Rectification & filtering	<0.2 mW	RFID, low power device
RF Signal [12]	unpredictable			
Biomass [13]	Controllable,	Microbial fuel cells	$153~\mathrm{mW/m^2}$	Underwater sensor
	predictable			

- Such energy harvesters are cost-effective, due to their decades of lifetime and almost negligible maintenance expenditure. The main cost of solar/wind energy harvesters originates from the deployment stage, which has been decreasing dramatically in recent years.
- Many industrial companies are actively participating in developing solar and wind energy harvesters, e.g., Suntech, First Solar, Sunpower, and Trina Solar for solar energy, or GE Energy, Vestas, Siemens Wind Power, and Goldwind for wind energy.

Though solar and wind harvesters enjoy high harvesting rates and low cost, the time variation of the energy source poses challenges to solar/wind power generation. Fortunately it turns out that solar and wind are a good complement to each other. On daily timescales, high pressure areas tend to bring clear skies and low surface winds, which is favorable for solar harvesters, whereas low pressure areas tend to be windier and cloudier, and thus are good for wind harvesters. On seasonal timescales, solar energy peaks in summer, whereas in many areas wind energy is lower in summer and higher in winter. We will demonstrate such a complementary effect in the following case study.

A case study: We will use real solar and wind power generation data by the Elia Group in Belgium¹. The normalized energy profiles on daily timescales are shown first. Based on the measured data from 0:00 am, 15 June to 0:00 am, 17 June, 2014, the average solar/wind power is shown in Fig. 1 (a), where the EH rates are sampled (averaged) every 15 minutes. We see that the peak of the solar power always coincides with the valley of the wind power, and vice versa. Next we show the energy profiles on seasonal timescales. Based on the data from 0:00 am, 17 May 2013 to 0:00 am, 02 July 2014, the average solar/wind power, averaged every 15 days, is shown in Fig. 1 (b). We see that the solar power achieves its peak during June-August, while the wind power reaches its bottom. An opposite trend is observed during December-February.

This case study reveals that a combination of solar and wind energy is a good candidate for the energy source of SCBSs. Actually, BSs powered by hybrid solar-wind energy have already drawn great attention from the industry. For example, the Turkish mobile operator Avea, and the leading equipment vendor Huawei have shown great interest in such BSs. Particularly, Wind-Fi, a renewable energy BS designed by the Centre for White Space Communications, enables wireless networks to operate entirely on solar and wind energy, and achieves 99.98% reliability².

B. The Prospect of EH-SCNs

The above discussion demonstrates that EH technology, particularly solar and wind harvesters, is a viable green energy solution for SCNs. Therefore, the EH-SCNs in the near future may consist of solar-powered SCBSs, wind-powered SCBSs, hybrid solar-wind-powered SCBSs, EH-SCBSs powered by other energy sources, and conventional grid-powered SCBSs as well. EH-SCNs will not only reduce the deployment cost and energy bills for the operators, but will also be more environmentally friendly and thus can enable sustainable growth of wireless networks. An example of such a network is shown in Fig. 2.

Powering SCNs by EH sources will bring new design challenges. The network coverage and the operating reliability will be difficult to guarantee since harvested energy varies daily and seasonally. Adjustments in the communication protocols and transmission strategies will

¹Elia, Power generation, available online at http://www.elia.be/en/grid-data/power-generation.

²Centre for White Space Communications, WindFi: Renewable-Energy Wireless Basestations, available online at http://www.wirelesswhitespace.org/projects/wind-fi-renewable-energy-basestation.aspx.

be needed. In the following part of this paper, special attention will be paid towards addressing the upcoming design issues in network deployment as well as in network operation.

III. NETWORK DEPLOYMENT OF EH-SCNS

Network deployment is the first step towards designing an effective EH-SCN. A key question to ask is how many EH-SCBSs are needed? Thus, in this section we will investigate the impact of the SCBS density on network performance and cost, which will reveal some interesting tradeoffs in EH-SCNs. Other deployment issues will then be discussed.

A. Basic Tradeoffs

The density of an EH-SCN will determine its performance, as well as the network cost. Increasing the EH-SCBS density can improve the coverage and throughput, but it will also increase the deployment cost. On the other hand, with a low density of EH-SCBSs, more grid-powered SCBSs will be needed to maintain the coverage, which will consume more nonrenewable energy and increase the energy bills. In the following, we will provide simulation results to illustrate these tradeoffs. The outage probability will be adopted as the performance metric, which is the portion of users that cannot be successfully served.

- 1) Tradeoff Between Outage Probability and EH-SCBS Density: We will first consider to provide network coverage only with off-grid EH-SCBSs, i.e., without any support of the grid. We assume each user is associated with its nearest SCBS, and we will ignore co-channel interference as the main purpose is to guarantee network coverage. For each SCBS, energy arrives intermittently with an average EH rate P_{EH} . In each time slot, part of the harvested energy will be used to serve its users, while the remaining part will be stored in a battery with capacity C_B . To investigate the impact of C_B , we consider two extreme cases, i.e., $C_B = 0$ or $C_B = \infty$. The transmit power for each user is determined to satisfy its receive SNR requirement γ_{th} . We ignore the circuit power consumption of the SCBSs unless otherwise mentioned. Each SCBS will serve all of its associated users if the available energy is sufficient; otherwise, it maximizes the number of served users. The SCBS and user densities are denoted by λ_{BS} and λ_u , respectively. The tradeoff between the outage probability p_{out} and λ_{BS} is shown in Fig. 3 (a). Key observations can be drawn:
 - The outage probability decreases with λ_{BS} , but the decreasing rate reduces as λ_{BS} increases further. Specifically, to achieve $p_{out}=10\%$ in this EH-SCN with $\lambda_u=10^{-3}~\text{m}^{-2}$, we can deploy SCBSs with density $\lambda_{BS}\geq 1.7\times 10^{-4}~\text{m}^{-2}$ if each SCBS is with

- $P_{EH}=20$ mW when supported by a battery with large enough capacity, or with $\lambda_{BS} \geq 2.1 \times 10^{-4}$ m⁻² if each is without a battery. Both are within the typical network density range of the SCNs [14].
- The battery capacity has little influence on p_{out} when λ_{BS} is either very small or very large. When λ_{BS} is very small, as the harvested energy is insufficient almost all the time, the energy will be exhausted immediately after it arrives. On the other hand, if λ_{BS} is very large, the current harvested energy will be more than enough, and there is no need to consume the energy in the battery.
- Increasing either P_{EH} or λ_{BS} will reduce p_{out} . Meanwhile, interestingly, increasing λ_{BS} brings more performance improvement, which can be explained intuitively. Doubling λ_{BS} not only doubles the available energy in the whole network, but also reduces the transmission distances on average.
- 2) Tradeoff Between Grid Power Consumption and EH-SCBS Density: In this part, we will assume that all the SCBSs are on-grid SCBSs, that is, the power grid is retained as the backup energy source for each SCBS. With a stable power supply, it is easy to guarantee coverage, and thus the focus is on the impact of the EH-SCBS density on the grid power consumption. At each SCBS, the harvested energy will be exhausted first, and the grid power will be used only when necessary. The tradeoff between the grid power consumption P_G and λ_{BS} is shown in Fig. 3 (b). Key observations can be drawn:
 - The grid power consumption P_G decreases with the SCBS density λ_{BS} , and the optimal EH-SCBS density can be chosen to minimize the network deployment and operating expenditures. For example, assume the electricity price is \$0.1971/KWh, while each SCBS costs \$135, of which \$35 is for the 10 W photovoltaic cell³, and \$100 is for the BS equipment. Normally, the lifetime of EH-SCNs is around 10 years. Then, if $\lambda_u = 3 \times 10^{-3} \text{ m}^{-2}$ and $P_{EH} = 20 \text{ mW}$, we can find the optimal SCBS density as $7.5 \times 10^{-5} \text{ m}^{-2}$.
 - To reduce P_G , increasing λ_{BS} is more effective than increasing P_{EH} . The impact of C_B on P_G is negligible when λ_{BS} is extremely small or extremely large.
- 3) Tradeoff Between Outage Probability and Grid Power Consumption: Compared to off-grid SCBSs, on-grid SCBSs make it easy to guarantee coverage with a stable power supply, but they are more difficult to deploy due to the grid power supply, and they will also

³This value takes the circuit power consumption of an EH-SCBS into account.

increase the non-renewable energy consumption. In this part, we will consider an SCN with both off-grid and on-grid SCBSs, while the total density is fixed. By varying the density of off-grid SCBSs, we can achieve different tradeoffs between the outage probability and the grid power consumption. With the ratio of on-grid SCBSs, denoted as η , increasing from 0 to 1, the outage probability will decrease, while the grid power consumption will increase. The relationship between p_{out} and P_G is shown in Fig. 3 (c), from which we can make the following observations:

- Changing η can adjust the tradeoff between the outage probability and the grid power consumption. For example, when $\lambda_{BS} = 2 \times 10^{-4} \text{ m}^{-2}$, $P_{EH} = 40 \text{ mW}$, we can achieve the outage probability $p_{out} = 0$ with $P_G = 2.38$ W by setting $\eta = 1$. Alternatively, we can achieve $p_{out} = 0.08$ with $P_G = 1.46$ W by setting $\eta = 0.6$, i.e., replacing 40% of the on-grid SCBSs with off-grid SCBSs, we can reduce the grid power consumption by \sim 40% with a slight performance degradation.
- The outage probability scales linearly with P_G , as both p_{out} and P_G scale linearly with η due to the independent and identical settings for different SCBSs, such as their locations and EH rates.

B. Deployment Issues

The previous discussions on the three basic tradeoffs in EH-SCNs provide us with the following deployment guidelines:

- Satisfactory coverage can be guaranteed in EH-SCNs with a reasonable network density.
 By carefully determining the network density, we can not only balance between network performance and deployment cost, but also achieve a tradeoff between performance and grid power consumption.
- To improve the network performance or to save the grid power consumption, it is more effective to increase the SCBS density than to increase the EH rate of each SCBS (e.g., by deploying a larger solar panel).
- When the EH-SCBS density is extremely small or extremely large, battery capacity has little influence on the network performance or the grid power consumption.

So far, the considered scenarios are rather simplified. For example, co-channel interference between users is ignored. The BS power consumption model is also ideal, as only the transmit power is considered, while in practice, for a femto BS, when the transmit power is 25 mW, around 5.2 W is consumed by the whole BS [9]. Therefore, a more detailed investigation will

be needed. One useful tool for network deployment is the spatial network model, as adopted in [8] and [14]. Such a network model can help to provide analytical results for performance evaluation, which may then provide guidelines for network deployment and avoid the time-consuming simulations. Moreover, we need to take realistic physical and social factors into consideration. Generally, BS locations can be adapted to the spatial traffic profile, i.e., more SCBSs should be deployed in the traffic hotspots to meet the high communication demand. Moreover, for a given location, the EH source should be chosen according to the ambient energy availability and their economic costs. For instance, a wind-powered SCBS is preferred to solar-powered SCBS at the seashore due to the abundant amount and the installation convenience of wind energy.

IV. NETWORK OPERATION OF EH-SCNS

In the last section, we investigated the deployment issues in EH-SCNs with simplified network operations. In a practically deployed EH-SCN, the network operation should be carefully designed to optimize the network performance. Due to the spatial and temporal variations of the EH conditions, the network operation strategies for conventional grid-powered SCNs are no longer applicable to EH-SCNs. In this section, with the joint power assignment and cell association problem as an example, we will illustrate the unique design challenges and some promising methodologies for EH-SCN network operations.

A. Power Assignment and Cell Association in EH-SCNs

Introducing EH-SCBSs will bring unique challenges for the SCBS power assignment and cell association problem, i.e., determining which SCBS each mobile should be associated with, and at which power level each SCBS should choose to transmit the signal. In particular, the following aspects should be considered:

- To incorporate the temporal and spatial variation of the available energy. In conventional SCNs, fixed cell association is normally adopted, e.g., the users are associated with their nearest SCBSs [14]. In SCNs, the temporal and spatial variation of the available EH source makes fixed association inapplicable, and a given user will need to be associated with different SCBSs during different periods. Thus, the design of cell association policies should balance the energy utilization of different SCBSs.
- To incorporate the coupling among different users/SCBSs. For a given SCBS, if it allocates a too high transmit power to serve one user, it may easily exhaust its available

energy and may not be able to serve other users. Thus some of its users need to be offloaded to other SCBSs, the available energy of which may be quickly depleted. This coupling among users/SCBSs renders power assignment of each SCBS and cell association quite complicated in EH-SCNs.

To demonstrate these aspects in more detail, we will next consider two specific design problems.

1) Performance Optimization for Off-grid EH-SCNs: We first consider an EH-SCN with M off-grid EH SCBSs and K mobile users, where each user is served by one SCBS in each time slot. To provide satisfactory performance to these users, an efficient joint cell association and power assignment policy should be developed. For simplicity, we assume a constant EH rate for each SCBS, but different SCBSs may have different EH rates. The design objective is to maximize the minimum average signal-to-noise ratio (SNR) among the K users, and thus, fair performance can be provided. This problem can be shown to be NP-hard. To reduce the computational complexity, we propose a low-complexity sub-optimal solution based on the threshold-bisection algorithm proposed in [15]. The proposed method will not only balance the energy usage at different SCBSs, but also take the future available energy at each SCBS into consideration, i.e., it considers both spatial and temporal energy variation.

To show the effectiveness of the proposed method, we introduce a performance upper bound and two baseline policies. The upper bound is obtained by allowing multiple SCBSs to jointly serve all the users using distributed beamforming, denoted as 'distributed BF'. The first baseline policy adopts distance-based cell association, where each user is served by its nearest SCBS. The second one adopts SNR-based cell association, where each user will be associated to the SCBS that provides the highest receive SNR with the available energy. The performances of different policies are shown in Fig. 4. Key observations can be drawn:

- The proposed solution greatly outperforms both baseline policies and achieves performance close to the upper bound.
- The distance-based policy suffers performance loss as it neglects the spatial variation of available energy at different SCBSs. Therefore, conventional cell association strategies cannot be directly adopted in EH-SCNs.
- The SNR-based policy performs better than the distance-based policy, as it utilizes information on both the distance and the current energy state. However, it still suffers performance degradation as it makes decisions based only on the current system state

and neglects the coupling in different transmission blocks as well as among different users.

In summary, the cell association policies should be redesigned for EH-SCNs and important aspects should be taken into consideration, including the temporal and spatial variation of the energy, and the coupling among SCBSs/mobile users. It is difficult to obtain optimal solutions, but effective sub-optimal solutions can be developed by considering the unique properties of EH-SCNs.

- 2) Grid Power Minimization for On-grid EH-SCBSs: In this part, we will consider an SCN consisting of both EH-SCBSs and grid-powered SCBSs. The design objective is to minimize the power consumption of grid-powered SCBSs by adaptive cell association. For simplicity, we will assume only one of the M SCBSs is powered by the grid, and we focus on the single-user case. All other assumptions are the same as the previous design problem. For this problem, we have obtained the following two optimal transmission strategies:
 - The Save-Transmit Strategy: For this solution, there exists a critical time slot, before which the user is served by the grid-powered SCBS, while afterwards, the EH-SCBSs take turns to serve the user. This strategy reflects an innate characteristic of EH systems, i.e., with a given number of time slots to use EH-SCBSs, deferring these time slots will not deteriorate the performance. However, non-causal EH information is required to obtain the critical time slot index.
 - The Greedy-Transmit Strategy: For this solution, in each time slot, if possible, the user will be served by one of the EH-SCBSs that has enough energy. Otherwise, the user is served by the grid-powered SCBS. This solution is extremely simple, as the decision in each time slot only depends on the current energy state of each EH-SCBS, irrespective of the future EH information.

We illustrate these two optimal transmission strategies in Fig. 5 with M=2. The upper part of Fig. 5 shows the save-transmit strategy, i.e., the user is served by the grid-powered SCBS from time slot 1 to 4, and then by the EH-SCBS from time slot 5 to 10 (the critical time slot index is 4). The lower part of Fig. 5 shows the greedy-transmit solution, where the user is served by the EH-SCBS so long as it has accumulated enough energy to support the transmit power. In both solutions, the user is served by the grid-powered SCBS in four time slots, i.e., both consume the same amount of grid power.

These two solutions are typical transmission strategies for EH communication systems. With a low complexity and a simple operation, surprisingly, they are optimal for the considered problem. Though the optimality may be lost in more general cases, they can still serve as heuristic methods and provide low-complexity and sub-optimal solutions.

B. Other Design Problems

The above discussions of cell association shed light on the operation issues in EH-SCNs, and provide some potential solutions. In general, the design problems in EH-SCNs will be more challenging than in conventional SCNs, and their unique characterizations, especially the impact of energy profiles, should be taken into consideration. Such policies as save-transmit and greedy-transmit can help develop efficient transmission policies, which in certain cases can be shown to be optimal. There are many other design problems to be addressed, including but not limited to the following:

- **Sleep Control:** When taking the circuit power of an SCBS into consideration, the energy efficiency of EH-SCNs can be effectively improved by sleep control, i.e., to adaptively switch off some SCBSs.
- User Scheduling: When an EH-SCBS is serving multiple users, how to schedule these users is vital for the network performance. As the available energy of each EH-SCBS accumulates over time, probably the users with better channel conditions should be served earlier, while the optimal policy requires further investigation.
- Channel Estimation: Channel information is important for wireless communications. However, due to the limited available energy in EH-SCNs, the energy spent on channel estimation and data transmission should be balanced. Moreover, it is also critical to decide when to perform channel training based on the time-varying EH profile.

V. CONCLUSIONS

In this article, we conducted a comprehensive study of EH-SCNs, including the feasibility analysis, network deployment investigation, and network operation design. Among potential EH sources, we found that the combination of solar and wind energy is a good candidate to power SCNs. To provide network deployment guidelines for network deployment, three basic tradeoffs between the network performance, EH-SCBS density, and grid power consumption were investigated. For a given deployed EH-SCN, in order to optimize the network performance, special attention was paid to the network operation designs in EH-SCNs. Throughout

the paper, distinctive challenges of EH-SCNs are highlighted, and novel design methodologies are proposed. Open research problems are identified which deserve unremitting efforts to promote faster, greener and more flexible EH-SCNs.

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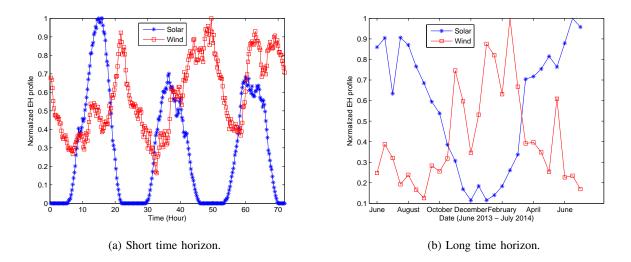
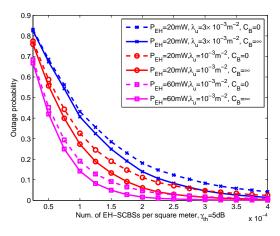
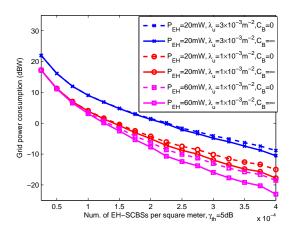


Fig. 1: Normalized solar and wind energy profiles.

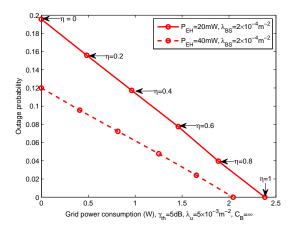


Fig. 2: A sample EH-SCN.





- (a) Outage probability vs. SCBS density.
- (b) Grid power consumption vs. SCBS density.



(c) Outage probability vs. grid power consumption.

Fig. 3: Basic tradeoffs in the EH-SCNs.

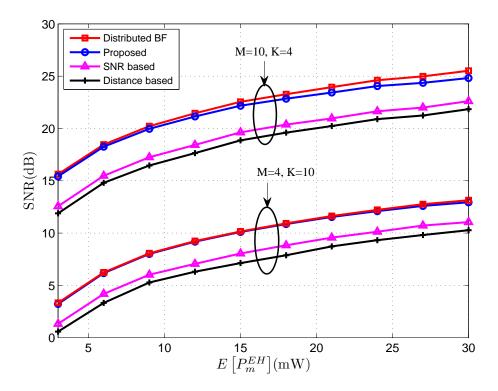


Fig. 4: Comparisons of different power assignment and cell association policies.

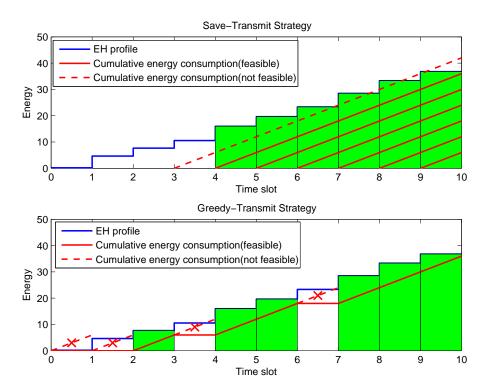


Fig. 5: Illustration of the Save-Transmit and Greedy-Transmit strategies (the user is served by the EH-SCBS in the shaded time slots, and the slope of the curve represents the transmit power).