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Power-Availability-Aware Cell Association for Energy-Harvesting Small-Cell Base Stations

Fanny Parzysz, *Member, IEEE*, Marco Di Renzo, *Senior Member, IEEE*,
and Christos Verikoukis, *Senior Member, IEEE*

Abstract—Energy harvesting brings a key solution to the increasing energy bill and environmental concerns but, at the same time, potential energy shortage may deteriorate the network availability. In this paper, we analyze the performance of off-grid small-cell base stations (scBS) with finite battery capacity and design a new power-availability-aware cell association based on periodical broadcast of the scBS battery level. Each mobile terminal (MT) targets its own set of available scBSs before association, i.e., the set of scBSs that can guarantee service provided 1) the scBS battery level; 2) the power required to satisfy a received power constraint at each MT, given the scBS-MT distance and the shadowing attenuation; and 3) the estimated power consumed to serve other MTs potentially associated to the same scBS, which is computed using stochastic geometry tools. Next, we develop for it a tractable performance analysis and derive closed-form expressions for the probability of power outage and the coverage probability. By dynamically adapting to the fluctuations of the base station battery and the MT received power requirement, the proposed cell association allows a more even distribution of the available energy in the network, brings robustness against harvesting impairment and thereby, significantly outperforms conventional strategies.

Index Terms—Cellular networks, energy harvesting, cell association, power availability, downlink transmission, power outage, stochastic geometry, Markov chain.

I. INTRODUCTION

THE ongoing deployment of low-powered, low-coverage and low-cost small-cell base stations (scBS) has boosted the performance of cellular networks and is shaping future 5G architecture [1], [2]. To conform to increasing environmental concerns while providing self-sustainability, energy harvesting technologies have been spurred not only for mobile terminals (MT) but also for access points and base stations. Conventional cell association policy is generally designed for on-grid networks, with unlimited power supply, and is not

suitable for base stations powered by unpredictable sources. As pointed out in [3] and [4], they do not make sparing use of the energy resource and may rapidly discharge the battery, leading to network availability degradation and reduction in the number of served users. Thus, it is necessary to design novel strategies tailored to the randomness of the harvesting process and to the battery-limited constraint at base stations.

Contributions: We design a new cell association for downlink small-cell networks with off-grid energy-harvesting base stations where: (i) each MT targets its own set of scBSs eligible for association using a *power availability criteria* and (ii) effectively associates to one of them. Then, (iii) each scBS selects for service the associated MTs, in accordance with its actual battery level. The proposed power availability criteria adapts each scBS-MT association pair to the scBS battery level and the transmit power required to satisfy a received power constraint at each MT, as a QoS requirement. In addition to path-loss and shadowing, it accounts for the power required by *other* MTs potentially associated to the same scBS. Such criteria remains simple and practically feasible as it is computed independently at each MT and only requires periodical broadcast of the scBS battery level.

To analyze the performance of the proposed cell association, we develop a comprehensive framework using a stochastic geometry approach, together with a Markov chain modeling for the battery. We compute closed-form expressions for both the probability of power outage and the coverage probability. In addition, a general result is derived to calculate the probability that a base station consumes *in total* exactly m power units. It allows to evaluate the power consumed to transmit data to several users simultaneously, but also to discard the assumption of full-power transmission for the computation of the received interference. Finally, simulations show that the proposed user association strategy achieves significant outage reduction, is less impacted by a decrease in the energy harvesting rate than conventional policies and is particularly robust against bursty energy arrivals.

Paper organization: The literature on the topic is reviewed in Section II. The network model and assumptions are described in Section III. In Section IV, we present the novel cell association, formulate the problem raised by the computation of its performance and describe the methodology considered to solve it. The performance is analyzed in Sections V, VI and VII and simulated in Section VIII. Section IX concludes this paper.

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F. Parzysz is with Department of Information and Communication Technologies, Universitat Pompeu Fabra, Barcelona 08018, Spain (e-mail: fanny.parzysz@ieee.org).

M. Di Renzo is with the Laboratoire des Signaux et Systèmes, CNRS, Centrale Supélec, Université Paris-Saclay, 91192 Paris, France (e-mail: marco.direnzo@l2s.centralesupelec.fr).

C. Verikoukis is with the Telecommunications Technological Centre of Catalonia (CTTC/CERCA), Barcelona 08860, Spain (e-mail: cveri@cttc.es).

II. RELATED WORK

A. Cell Association in Energy-Harvesting Networks

The optimization of cell association has mainly targeted energy-harvesting networks with centralized control, where global channel state information (CSI) and battery state information (BSI) are available at a central, possibly virtual, node. A rich literature has proposed algorithms to maximize, for example, the user signal-to-noise ratio, the rate or the resource utilization accounting for the BS battery level and the energy harvesting process [5]–[7]. Whereas the proposed solutions provide relevant performance benchmarks, such optimization problems are generally NP-hard, (sub)optimal solutions are found at high computational cost and closed-form performance results are hardly derived for large-scale networks.

Distributed association schemes have been proposed as a response to this issue. Each MT associates to a BS independently of other MTs and based on local CSI/BSI only. Such information shortage, coupled with the uncertainty in the energy arrivals at BSs and in the other MT association decision, renders distributed association more challenging as highlighted in [8]. Letting the possibility for MTs to attach to a BS that cannot guarantee service, due to a battery level too low given the traffic demand, leads to severe power outage or service denial. This issue is further discussed in the following and is addressed throughout this paper.

B. Network Power Availability

A device equipped with energy harvesting capability may extract energy from a variety of natural or man-made sources, most commonly solar radiations [4], [9], [10] and more recently, radio-frequency signals [10]–[16]. Whatever the considered harvesting technology and related distribution for random energy arrivals, a fundamental aspect of networks with battery-constrained BSs lies in their power availability. To guaranty service, one solution lies in considering hybrid base stations, provided with both harvesting facilities and access to the power grid, and analyze the system performance by including the power price from electrical grid, as done in [17]. Different from such an approach, we focus on base stations solely powered from energy harvesting. In this case, performance can be significantly improved by controlling the set of BSs eligible for association, such that MTs are not necessarily associated with their nearest BS and may be offloaded from BSs with low energy resource to BSs with sufficient battery.

Numerous works have focused on the possibility to activate / deactivate transmitters following their battery level and energy consumption. Such approach has been considered notably for relay selection [14]–[16], where relays participate to data transmission only if they have sufficient energy stored in their battery. However, these works consider only a single source-destination pair. Larger-scale networks have been considered in [18]. In this, MTs opportunistically associate with the activated base stations providing the highest received signal strength. Yet, such process relies on a fixed battery threshold and the resulting on/off decision applies equally to all MTs, independently of their power requirements and channel quality.

Thus, a BS can be switched off even if it could serve MTs with low power requirements.

With another perspective, biased cell association is analyzed in [19] and [20], i.e. the relative cell coverage is extended or shrunk depending on the BS-MT distance. While such solution accounts for the MT power requirement, the proposed bias is the same for all BSs and fails in capturing the battery fluctuations. The coupling existing between the user requirement and the battery level regarding cell association is still an open research field in energy harvesting networks, as pointed out in [4], and is investigated in this paper.

C. Acquisition of the Battery Level Information

It is widely assumed that data transmission and energy harvesting can occur simultaneously and that only one MT is served at a time. Such model has been considered for uplink transmissions with energy-harvesting MTs in [19] and [21] and for downlink transmissions in [18] and [20]. However, such assumption remains questionable for scBSs simultaneously serving some tens of users and is not applicable once BSI is required at users. In our framework, targeting the set of base stations eligible for cell association is conditioned by the battery level, leading to the question of BSI acquisition.

Several research works have proposed optimal transmission strategies assuming causal and non-causal knowledge of the battery level [22]–[24]. Yet, in practice, obtaining non-causal information is not feasible and perfect real-time knowledge of the battery level necessitates excessive signaling overhead, low latency information exchange and tight synchronization. Given the high variability of energy arrivals, traffic demand and user mobility, continuous broadcast from all BSs of their instantaneous battery level (which varies at each power unit arrival and consumption) is extremely costly. This raises the double issue of the accuracy and the frequency of battery information exchange. While robust designs have been proposed to account for imperfect battery knowledge, notably for resource allocation schemes [9], [25], a fully-distributed cell association scheme has been proposed in [13] where MTs successively associate to base stations that are expected to guarantee a minimum rate for every data packet. In [13], users do not have any information about the effective channel quality, the harvested energy nor the traffic intensity, but only know about their distribution, for which a generic model is proposed.

In this paper, we address the issue of BSI acquisition with a novel perspective by considering periodical battery information broadcast. Contrary to real-time information exchange, more than one MT can associate to the same BS based on the same battery information, leading to unique challenge, notably to design an efficient power availability criteria.

III. SYSTEM MODEL AND ASSUMPTIONS

We describe in this section the network model, the assumptions for energy harvesting and the battery model. We invite the reader to refer to Table I which summarizes the notation used in this paper. In particular, the index k will always refer to a small-cell BS, j to a MT and l to a battery state.

TABLE I
CONSIDERED NOTATIONS

Indexing	k/j l/l^*	Considered scBS / MT Power buffer state / Lowest buffer state providing availability
PPP / intensity	Φ_B / λ_B	scBS location in the network
	Φ_B^* / Λ_B	Set of the p_{k0} 's $\forall k$, i.e. Required transmit power from any scBS to MT ⁽⁰⁾
	$\mathcal{A}_j / \Lambda_B^{(A)}$	Subset of the p_{k0} 's for which scBS _k is available for MT ⁽⁰⁾
	Φ_{MT} / λ_{MT}	MT location in the network
	$\Phi_{MT}^* / \Lambda_{MT}$	Set of the p_{0j} 's $\forall j$, i.e. Required transmit power from scBS ⁽⁰⁾ to any MT
Power	$\mathcal{S}_k / \Lambda_{MT}^{(S)}$	Subset of the p_{0j} 's for which scBS ⁽⁰⁾ serves MT _j
	p_{kj} / P_{Rx}	Power required to send data from scBS _k to MT _j / Received power constraint $\forall j$
	$P_k^{(T)} = \sum_{j \in \mathcal{S}_k} p_{kj}$	Total transmit power of scBS _k
	$\tilde{P}_{k \setminus j}^{(T)}$	Estimated total transmit power from scBS _k to all MTs requiring less p_{kj}
	$P_k^{(A)} / P_k^{(H)}$	Available power / Harvested power at scBS _k
	$p_l^{(cov)}$	Maximum possible required transmit power when $P_k^{(A)} = l$
	P_{max} / L	Power buffer capacity in watts / in power units ($\forall k$)

A. A PPP-Based Network

To analyze the performance of the proposed strategy for cell association, we consider a downlink cellular network consisting of one tier of small-cell base stations (scBS). As most of small-cell infrastructures are opportunisticly deployed, resulting in irregularly-shaped networks, modeling the node position as random variables allows to analyze the network performance using tools of stochastic geometry and alleviates the need for extensive simulations. In this work, BSs are thus distributed according to an independent homogeneous Poisson point process (PPP), with density λ_B and denoted as Φ_B . Figure 3 illustrates a potential realization for the BS location, where the cell edges are based on the Voronoi tessellation resulting from associating with the closest BS.

As a widely considered assumption [18]–[20], [26], mobile terminals are as well distributed according to a homogeneous PPP, independent of Φ_B . It is denoted as Φ_{MT} and has density λ_{MT} . This implies that, at each time slot, a random number of MTs is taken from a Poisson distribution and their locations are uniformly distributed over the simulated network area. Given the extreme densification of next-generation cellular networks, we assume that each MT can connect to more than one base stations, as done for example in [27] and [28].

B. Channel Model for Data Transmission

Downlink transmissions are assumed throughout the analysis presented in this paper. The channel model accounts for path-loss, shadowing and fast fading. All links are assumed mutually independent and identically distributed. First, let $l(r_{k,j}) = \kappa r_{k,j}^\alpha$ be the path-loss from scBS_k to MT_j, where $r_{k,j}$ is the distance between them, κ is the free-space path-loss at a distance of 1m and α is the path-loss exponent.

Second, the shadowing attenuation $\chi_{k,j}$ from scBS_k to MT_j follows a log-normal distribution with p.d.f

$$f_{\chi_{k,j}}(w) = \frac{\zeta}{w\sigma\sqrt{2\pi}} \exp\left(-\frac{(10\log_{10}(w) - \mu)^2}{2\sigma^2}\right) \quad (1)$$

where $\zeta = 10/\ln(10)$ and where μ and σ are in dB.

Finally, the channel from scBS_k to MT_j is subjected to a random complex channel gain $|h_{k,j}|^2$ with exponential distribution of parameter ν and a p.d.f. given by

$$f_{h_{k,j}}(w) = \nu \exp(-w\nu) \quad (2)$$

As in [18] and [13], served MTs are orthogonal, such that there is no intra-cell interference. The number of sub-channels available at each BS is assumed large enough to accommodate any MT requiring service, as long as sufficient power is available. Such assumption provides a tractable benchmark for performance analysis, where the system is power-limited rather than load-limited.

C. Assumptions on the Power Requirement

Cell association rules based on fixed transmit power may rapidly discharge the battery and reduce the number of served users [4]. One way to minimize the power consumption is to make the transmit power as low as possible while satisfying user quality constraints. In this work, we propose an energy-minimization approach for power allocation and consider that scBSs adjust their transmit power to ensure that the power received at any served user is equal to a given received power constraint P_{Rx} , as a QoS requirement. Thereby, a scBS with low available power can nonetheless serve nearby users, with low power requirement. We define p_{kj} as the transmit power of scBS_k to sent data to MT_j, while satisfying P_{Rx} , i.e.

$$p_{kj} = P_{Rx} \frac{l(r_{k,j})}{\chi_{k,j}}. \quad (3)$$

Such value of the BS transmit power is also estimated by each user to target available BSs and associate with one of them. Since fast fading can be hardly tracked for cell association, it is not included in the computation of p_{kj} . Note that p_{kj} can also be interpreted as the transmit power consumed by scBS_k to send data to MT_j over a sufficient period of time such that fast fading is averaged out.

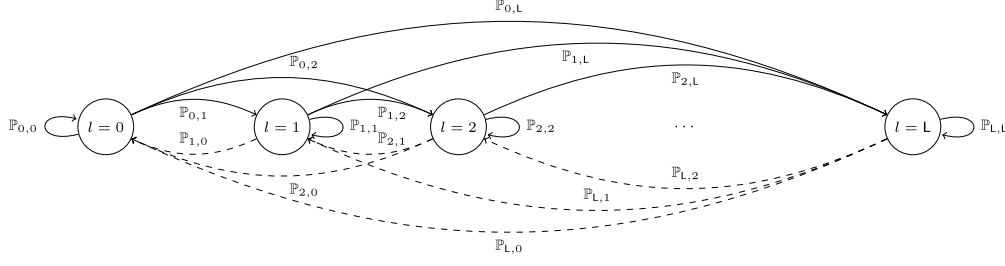


Fig. 1. Modeling the battery states $P_k^{(A)}$ of $scBS_k$ as a Markov chain.

Remark: In addition to the transmit power, the overall BS power consumption generally includes the power dissipated in circuitry for data transmission, signal processing, network maintenance and site cooling. It is expressed by:

$$P_k^{(\text{Total})} = \sum_j (\eta p_{kj} + P_{(\text{dsp})}) + P_{(\text{idle})} \quad (4)$$

where η refers to the RF amplifier loss, $P_{(\text{dsp})}$ to the per-user fixed power offset consumed for signal processing and $P_{(\text{idle})}$ to per-BS idle power consumption. Even if the expression for p_{kj} in Eq. (3) only accounts for the BS transmit power, the proposed framework can be generalized to more realistic models. Indeed, for both the computation of the availability checking and performance analysis, the factor η can be directly included in the power constraint P_{RX} and $P_{(\text{idle})}$ can be deduced, without loss of generality, from the battery level which is broadcast at each time slot. Finally, including $P_{(\text{dsp})}$ in the proposed framework only requires slight modification of the power availability criteria described in Subsection IV-B.1. Yet, its actual value is usually low compared to ηp_{kj} and $P_{(\text{idle})}$, and can be reasonably neglected for performance analysis.

D. A Discrete Model for the Power Buffer

We assume as in [18] and [13] that all $scBS$ s are harvesting energy from the environment, e.g. using wind harvester or solar panels. Each is equipped with a battery, or power buffer, with maximal capacity P_{max} . MTs are assumed powered by conventional batteries, charged by users themselves, and their energy limitation is not considered in this paper.

To successfully target the set of available BSs, MTs require to know how much power is stored in their battery. Such information can be easily broadcast by BSs, as part of signaling in control channels. Yet, to limit the resulting extra overhead, we assume that such broadcast is only performed periodically, as depicted in Figure 2. We refer to the time duration between two battery broadcasts as a time slot. Let t denote for the beginning of a time slot, and τ for its duration.

In addition, $P_k^{(A)}(t)$ refers to the amount of power that is available in the buffer of $scBS_k$ at instant t and broadcast towards MTs for cell association. $P_k^{(H)}(t)$ denotes for the amount of harvested power and $P_k^{(T)}(t)$ for the power required by associated users (equally the total power consumed by the considered $scBS$) during this time slot. Then, the following

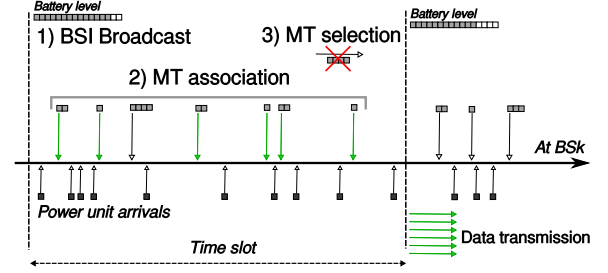


Fig. 2. Time slot model.

conditions hold:

$$\forall t, k \begin{cases} P_k^{(A)}(t) = P_k^{(A)}(t - \tau) - P_k^{(T)}(t) + P_k^{(H)}(t) \\ P_k^{(A)}(t) \leq P_{\text{max}} \text{ and } P_k^{(T)}(t) \leq P_k^{(A)}(t - \tau) \end{cases} \quad (5)$$

For sake of readability, the time slot index (t) is dropped in next sections if there is no ambiguity.

1) *Markov Chain Model:* We aim to analyze the variation of the battery level $P_k^{(A)}$ between t and $t + \tau$, $\forall t$. To do so, we propose the following model. Both the harvested and consumed powers are continuous random variables and so is the amount of power that is stored in the battery. Since such assumption is not tractable for analysis, we consider an approach similar to [21], [29] by discretizing the states of the battery into a finite number of levels, as depicted in Figure 1. As a consequence, the harvested and consumed powers are discretized as well. Note that the stochastic processes of both of them only depend on the buffer state at previous time slot, such that the battery forms a finite-state Markov chain. We respectively define L and ε as the highest battery level and the step size (or power unit), i.e. $P_{\text{max}} = \varepsilon L$. The transition probability matrix of the battery Markov chain is denoted as $\mathbf{P} = [\mathbb{P}_{lq}^{\rightarrow}]$, where $\mathbb{P}_{lq}^{\rightarrow}$ stands for the probability to go from state l to state q from one time slot to the next one. The probability that the battery has l power units is denoted as v_l and the probability vector of the battery states as $\mathbf{v} = [v_0 v_1 \dots v_L]$.

As stated in Eq. (5), the random variations of $P_k^{(A)}$ are fully characterized by analyzing the probability to harvest m power units ($P_k^{(H)} = m$) and to consume n power units ($P_k^{(T)} = n$), as done in the following two subsections.

2) *Model For Energy Harvesting (Battery Charge):* Without loss of generality, a general energy harvesting model is considered, where N_e power units are harvested at a time and where the power arrivals follow a Poisson process of intensity λ_e . Both parameters N_e and λ_e allows to model the burstiness of

the harvesting process. The probability $\mathbb{P}_H(mN_e)$ to harvest mN_e units over duration τ is independent from the current battery state and is given by:

$$\mathbb{P}_H(mN_e) = \mathbb{P}\left(\left\lfloor \mathbf{P}_k^{(H)} \right\rfloor = mN_e\right) = \frac{(\lambda_e \tau)^m}{m!} \exp(-\lambda_e \tau). \quad (6)$$

As shown in [30] and [9], solar energy arrivals are efficiently modeled as stochastic Markov processes, and more specifically Poisson process [11]. In this case, the parameters N_e and λ_e are determined by the quantity of sunlight, cloud coverage, air density, temperature, but also the size of the photo-voltaic panel [11]. We also highlight that the analysis proposed in this work is valid for other harvesting processes, by considering other function \mathbb{P}_H .

3) *Model For Energy Consumption (Battery Discharge)*: To model the battery discharge, a birth-death process has been proposed in [14]–[16] and [18], where users consume exactly one power unit and where the battery level is updated at each new data transmission. Yet, such a model cannot be applied in our framework. First, each user has a different power requirement, as stated in Eq. (3), implying that it is not sufficient to consider the number of users currently being served to model the battery discharge. Moreover, in our case, updated battery levels are *not* broadcast after each new user association, such that the battery decrease potentially accounts for transmission towards *more than one* user.

To compute the probability to consume n power units ($\mathbf{P}_k^{(T)} = n$) and characterize the transition probability matrix \mathbf{P} , the power consumed by *all* users associated during this time slot should be analyzed.¹ The amount of elementary power p_{kj} consumed to send data from a given scBS $_k$ to MT $_j$ is rounded up to the nearest battery unit and the probability $\mathbb{P}_T(n | l)$ to consume a *total* of n power units given that scBS $_k$ has l power units in its battery is equal to $\mathbb{P}\left(\mathbf{P}_k^{(T)}(t) \simeq \sum_j \lceil p_{kj} \rceil = n | l\right)$. Its computation is one of the main issues solved in this paper.

Remark 1: The arrival order within a time slot is not considered and MTs are selected in ascending order of their power requirement.

Remark 2: Increasing the battery broadcast period, i.e. the time slot duration τ , suggests a higher λ_{MT} , since more MTs can request cell association during the same slot. This is discussed in Section VIII.

IV. PROPOSED CELL ASSOCIATION AND METHODOLOGY

This section describes the proposed energy-aware cell association with BS availability checking and presents the methodology considered for performance analysis.

A. Overview of the Proposed Cell Association

In a network deprived of access to the power grid, a BS with low battery may not be able to guaranty service. By knowing the BS battery state and by comparing such value with the energy required to meet the received power constraint P_{RX} , users can avoid associating with a nearby BS in energy shortage and prefer another with higher battery level, even if such

scBS is farther. The proposed cell association accounts for both aspects of the scBS available power and the MT required transmit power, as expressed in Eq. (3), and can be interpreted as an energy-oriented offloading technique. We further assume that scBSs are not interacting nor cooperating.

1) *Procedure*: The proposed strategy is depicted in Figure 2 and is performed in three steps, over each time slot.

- *At the beginning of a time slot*, scBSs broadcast their battery state, for example by using the PDCCH (Physical Downlink Control Channel) of the LTE frame.

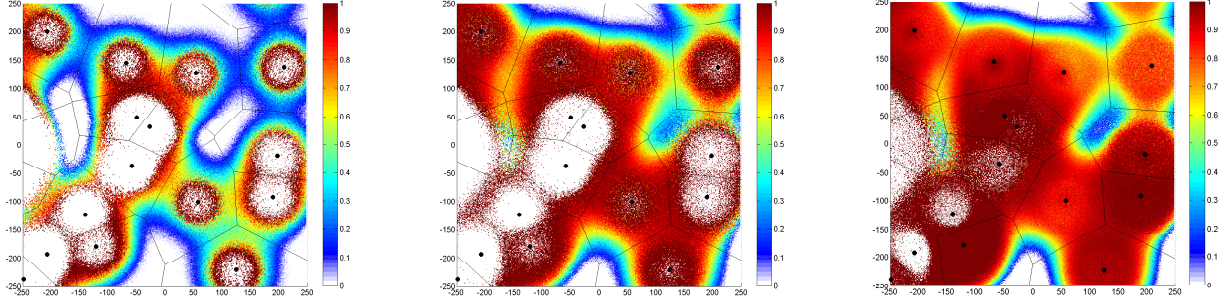
- *During this time slot*, when a new MT requests service, cell association is performed in two steps: 1) Power availability and 2) Effective cell association. First, this MT checks if the transmit power required to satisfy the received power constraint P_{RX} is compatible with the battery level of the neighboring scBSs, as announced by broadcast. By doing so, each MT targets a subset of scBSs which are eligible, or available, for cell association. Second, each MT associates to one of the available small-cell BSs. It chooses the one which consumes the least transmit power while meeting P_{RX} .

- *At the end of the time slot*, a third step specific to the considered energy-constrained context must be considered before data transmission. Due to power limitation, a scBS may not be able to serve all associated MTs, if too many are associated to it despite power availability checking. Thus, each scBS proceeds to MT selection. Unselected MTs are denied service and wait for the next time slot, with updated information on the battery state, to target newly available BSs and perform once again association. Nevertheless, the proposed availability criteria results in a very low probability to be denied service once associated, as shown in Section VIII.

2) *Principal Advantages*: Figure 3 illustrates the gain in the probability of power outage that is achieved by the proposed energy-aware cell association (namely, scheme “ \mathcal{A} ”) over conventional association without availability checking (namely, scheme “*w/o* \mathcal{A} ”). For each MT location in the network, we compute the ratio $\left(\mathbb{P}_{out}^{(w/o\mathcal{A})} - \mathbb{P}_{out}^{(\mathcal{A})}\right) / \mathbb{P}_{out}^{(w/o\mathcal{A})}$. As observed in Figures (a) and (b), the proposed strategy significantly improves the performance at cell edge, even when the energy harvesting rate is low compared to the cell coverage (Fig. (a)). When the energy arrival is bursty ($N_e = 80$ - Figure (c)), performance gain is generally higher and obtained in a larger part of the network. Indeed, the availability criteria follows the BS battery variations, such that users are dynamically distributed among neighboring scBSs as a function of energy arrivals. This is further discussed in Section VIII-C.

This reduction in the probability of power outage provides fairness in the user service, as less energy is consumed to serve cell-center users, implying that more energy is available to serve cell-edge users with the same received power constraint. Contrary to network-optimized association policies, the proposed strategy can be easily implemented and does not require extra signaling overhead (excepting BS battery broadcast), e.g. link quality exchange, nor tight BS synchronization/cooperation, nor heavy computation at a central node, which all consume significant energy as well.

¹For analysis, we assume that data transmission effectively occurs in the next time slot, as shown in Figure 2.



(a) $P_{R_x} = -60\text{dBm}$, $N_e = 1$, $\lambda_e = 5\% L/N_e$ (b) $P_{R_x} = -65\text{dBm}$, $N_e = 1$, $\lambda_e = 10\% L/N_e$ (c) $P_{R_x} = -65\text{dBm}$, $N_e = 80$, $\lambda_e = 10\% L/N_e$

Fig. 3. Gain in the probability of outage.

B. Description of the Proposed Cell-Association

1) *Set of Available Small-Cell BSs*: The power availability criteria characterizes the set of available scBSs and each MT determines its own subset of available scBSs as follows:

Definition 1: The subset of scBSs declared available by MT_j is denoted as \mathcal{A}_j (with \mathcal{A} for Available) and is given by:

$$\mathcal{A}_j \triangleq \left\{ \text{scBS}_k \in \Phi_B : p_{kj} + \tilde{P}_{k \setminus j}^{(T)} \leq P_k^{(A)} \right\}$$

where $\tilde{P}_{k \setminus j}^{(T)}$ refers to the *estimated* transmit power required by other MTs associated to scBS_k and selected before MT_j following the MT selection rule of Def. 3. It is computed as the expected sum of the power required by any other MT_i satisfying $p_{ki} < p_{kj}$, i.e.

$$\tilde{P}_{k \setminus j}^{(T)} \triangleq \mathbb{E} \left[\sum_{i \in \Phi_{k \setminus j}} p_{ki} \right]$$

where $\Phi_{k \setminus j} \triangleq \{ \text{MT}_i \in \Phi_{MT} : p_{ki} < p_{kj} \}$. The estimate $\tilde{P}_{k \setminus j}^{(T)}$ is computed later on in Eq. (7).

Insights for Definition 1: Several power availability criteria are possible for the scBS pre-selection rule. The simplest one would be to check if the required power p_{kj} does not exceed the battery level, i.e. $p_{kj} \leq P_k^{(A)}$ and $\tilde{P}_{k \setminus j}^{(T)} = 0$. Whereas such criteria is valid if the battery level is known at MTs in real-time, this is not adapted to the considered multi-user transmission context with periodical broadcast. Given the power constrains in Eq. (5), the *total* power of served MTs, i.e. $P_k^{(T)} = p_{kj} + \sum_{i \in S_k} p_{ki}$, with S_k the set of MTs served by scBS_k, has high probability to exceed $P_k^{(A)}$ with such availability criteria, leading to severe power outage. To avoid associating to a scBS that cannot guarantee service, a valid power availability criteria should accommodate the transmit power required by the other users served by scBS_k, i.e. $\sum_{i \in S_k} p_{ki}$, in addition to the power p_{kj} required by MT_j. However, the total consumption $P_k^{(T)}$ depends on the cell association of all MTs of the network which cannot be known in advance for computing the power availability criteria (non-causal information). An estimate of $P_k^{(T)}$ is thus required. If overestimated, the set of available scBSs may be excessively reduced. If underestimated, a scBS may be associated to more MTs than it can actually serve given its available power, as for the criteria $p_{kj} \leq P_k^{(A)}$.

As scBSs serve MTs in ascending order of required powers, it is sufficient to account only for the total transmit power of the served MTs that require less power than p_{kj} . In the proposed availability criteria, MT_j assumes that any other MT which requires less power than p_{kj} is associated with scBS_k, regardless of their effective cell association. The estimate $\tilde{P}_{k \setminus j}^{(T)}$ only requires to know the density of MTs λ_{MT} and the battery level $P_k^{(A)}$. Its value can be computed using stochastic geometry tools as follows:

$$\begin{aligned} \tilde{P}_{k \setminus j}^{(T)} &= \lambda_{MT} \Upsilon \frac{2/\alpha}{2/\alpha + 1} (p_{kj})^{\frac{2}{\alpha} + 1} \\ \text{with } \begin{cases} \Upsilon &= \pi \left(\frac{1}{P_{R_x} \kappa} \right)^{\frac{2}{\alpha}} \exp \left(\frac{2/\alpha}{\zeta} \mu + \frac{1}{2} \left(\frac{2/\alpha}{\zeta} \right)^2 \sigma^2 \right) \\ \zeta &= 10 / \ln(10) \end{cases} \quad (7) \end{aligned}$$

The proof of Eq. (7) is given in Appendix A.

Remark: Assuming a generalized power consumption model as described by Eq. (4), the per-user power consumed for signal processing at the serving BS can be included in the power availability criteria by adding $P_{(\text{dsp})} \Lambda_{MT}(p_{kj})$ to $\tilde{P}_{k \setminus j}^{(T)}$, where $\Lambda_{MT}(p_{kj})$ is the average number of MTs requiring less than p_{kj} . Yet, this does not modify the proposed analysis.

2) *Effective Cell Association*: Once available scBSs have been targeted, each MT effectively associates to one of them.

Definition 2: A mobile terminal MT_j associates with the available base station which consumes the least transmit power to satisfy the received power constraint P_{R_x} . It is denoted as scBS₀, with:

$$\text{scBS}_0 = \arg \min_{\text{scBS}_k \in \mathcal{A}_j} \left\{ P_{R_x} \frac{l(r_{k,j})}{\chi_{k,j}} \right\} = \arg \min_{\text{scBS}_k \in \mathcal{A}_j} \{ p_{kj} \} \quad (8)$$

This cell association is equivalent to associating with the small base station for which the received power is maximal, for a fixed transmit power equal to $\frac{1}{P_{R_x}}$.

3) *MTs Selection Rule*: To maximize the number of served MTs while satisfying the received power constraint for all of them, we consider the following approach:

Definition 3: Each small-cell BS selects mobile terminals to be served among the associated ones and in ascending order of their power requirement till all associated users are selected

or till the overall power consumption reaches the battery level. This subset of MTs is denoted as \mathcal{S}_k for scBS $_k$.

We will show that the probability to be associated but rejected is negligible for the proposed cell association.

Remark: Such MT selection strategy allows hard decision for the power availability criteria, which is not permitted by a random MT selection, where a small-cell base station can be declared available only with a given probability.

C. Problem Formulation and Methodology For Analysis

To analyze the performance of the proposed energy-aware cell association in terms of power outage and coverage probability, it is necessary to understand how the availability criteria, the effective association and the MTs selection rule affect the set of served MTs and the battery level and reciprocally, how the battery level determines the set of scBSs eligible for association. Although Monte-Carlo simulations offer wide possibilities for refined performance analysis, they suffer from two main drawbacks. First, they are time-consuming and their accuracy is significantly affected by the number of samples considered for simulations. Second, they confine the obtained conclusions only to the considered parameter settings and are hardly used for performance generalization. This motivates us to compute closed-form expressions for performance analysis, which is the object of the remainder of the paper.

The analytical approach considered in [18] to compute performance is based on the expected cell coverage, average number of served MTs and average transmit power consumption. Yet, it cannot be applied to the proposed scheme which accounts for their instantaneous fluctuations. Instead of averaging, the probability mass functions (pmf) of the battery states and of the number of power units consumed at each BS transmission are computed in this paper. To this end, we point out that the Markov chain formed by the battery levels converges to a unique stationary distribution solving:

$$\mathbf{v} = \mathbf{v}\mathbf{P} \quad \text{with} \quad \mathbf{1} = \mathbf{v}\mathbf{1} \quad (9)$$

where $\mathbf{1}$ is a all-ones vector and $\mathbf{v} = [v_0 v_1 \dots v_L]$ is the steady-state battery probability vector, of dimension $1 \times (L + 1)$.

Proof: The considered Markov chain is aperiodic and irreducible ($\mathbb{P}_{i,j} > 0, \forall i, j$, i.e. all the states communicate), with finite state space. Next, $\forall l, \sum_q \mathbb{P}_{lq}^{\rightarrow} = 1$ and, given that the energy harvesting and energy consumption processes are distinct and independent, $\mathbb{P}_{lq}^{\rightarrow} \neq \mathbb{P}_{ql}^{\rightarrow}, \forall l, q$, implying that the transition probability matrix \mathbb{P} is not symmetric. Consequently, it is row stochastic and not doubly stochastic. \square

The proposed analysis aims at solving such system. The main challenge lays in the computation of the transition probability matrix of the battery Markov chain $\mathbf{P} = \left[\mathbb{P}_{lq}^{\rightarrow} \right]$, of dimension $(L + 1) \times (L + 1)$, which is itself a function of \mathbf{v} and renders the system of equations in (9) non-linear. To solve such issue, we consider the following methodology. First, we analyze the conditions for availability and characterize the set of available BSs as a function of the probability vector \mathbf{v} (Subsection V-A). Next, we deduce the sets of MTs served by a given BS (Subsection VI-B). Based on such characterization,

we compute $\mathbb{P}_{lq}^{\rightarrow}, \forall l, q$ as a function of \mathbf{v} and propose an algorithm to solve Eq. (9) (Subsection VI-C). Finally, performance are computed (Section VII).

V. ANALYSIS OF THE PROPOSED CELL ASSOCIATION: THE USER'S PERSPECTIVE

This section is dedicated to the characterization of the set of available BSs and the probability of cell association.

A. Analysis of the Set of Available scBSs

Generalities: For analysis, the Slivnyak theorem allows considering a single typical small-cell base station, denoted as scBS $^{(0)}$, without loss of generality. Let's define Φ_{MT}^* as the point process of the p_{0j} 's $\forall j$, for this typical scBS. From the properties of displaced PPPs, scBS $^{(0)}$ sees the p_{0j} as distributed according to a non-homogeneous PPP on \mathbb{R}^+ with intensity $\Lambda_{MT}(p) = \lambda_{MT} \Upsilon p^{\frac{2}{\alpha}}$, as proved in Appendix A. Similarly, a typical mobile terminal, denoted as MT $^{(0)}$, can be considered for analysis. It sees the p_{k0} 's, $\forall k$ as distributed according to a non-homogeneous PPP, denoted as Φ_B^* , and of density $\Lambda_B(p) = \lambda_B \Upsilon p^{\frac{2}{\alpha}}$.

Given the power availability criteria of Definition 1 and the estimated power consumption of Eq. (7), the typical user MT $^{(0)}$ assumes that any other MT which requires less power than p_{k0} is associated with scBS $_k$. Denoting $\mathbf{P}_k^{(A)} = l$ power units, the availability criteria is equivalently defined as:

$$p_{k0} + \tilde{\mathbf{P}}_{k \setminus 0}^{(T)} \leq \mathbf{P}_k^{(A)} \Leftrightarrow g_A(p_{k0}) \leq l$$

$$\text{with} \quad g_A(p) = p + \lambda_{MT} \Upsilon \frac{2/\alpha}{2/\alpha + 1} p^{\frac{2}{\alpha} + 1} \quad (10)$$

Since $g_A(p+1) - g_A(p) > 1$, increasing the required transmit power by one power unit necessitates a much higher increase of the power available in the power buffer to account for all other MTs requiring only p .

We define $p_l^{(\text{cov})}$ as the maximum power that can be required by a MT served by a scBS having l power units in its battery, i.e. the maximum power satisfying the availability criteria:

$$p_l^{(\text{cov})} = g_A^{-1}(l) \quad (11)$$

$p_l^{(\text{cov})}$ can be interpreted in terms of power coverage. Any MT $_j$ for which $p_{kj} \leq p_l^{(\text{cov})}$ declares scBS $_k$ available for data transmission. Reciprocally, the MTs served by scBS $_k$ are solely located in this subset. Note that scBS $_k$ is necessarily unavailable for any MT $_j$ such that $p_{kj} > p_l^{(\text{cov})}$.

Likewise, the lowest buffer state l^* providing availability of scBS $_k$ for MT $^{(0)}$ is defined as:

$$l^* - 1 < g_A(p_{k0}) \leq l^* \Leftrightarrow p_{l^*-1}^{(\text{cov})} < p_{k0} \leq p_{l^*}^{(\text{cov})} \quad (12)$$

with p_{k0} the required power to transmit data from scBS $_k$ to MT $^{(0)}$. Using such notation, scBS $_k$ is declared available if its battery state l is greater than l^* . This occurs with probability:

$$\mathbb{P}_B^{(A)}(p_{k0}) = \sum_{l=l^*}^L v_l \quad (13)$$

where v_l is the probability to be in state l . Such probability allows to compute the intensity of available BSs.

Given that both scBSs and MTs are independently located, that energy is harvested independently at each base station and that the power availability checking is performed independently at each MT as well, each BS of Φ_B^* is declared available by MT⁽⁰⁾ with probability $\mathbb{P}_B^{(A)}(p_{k0})$.

Lemma 1: The subset \mathcal{A}_0 of small-cell base stations available for MT⁽⁰⁾ forms a PPP on $[0, p_L^{(\text{cov})}]$, with density

$$\begin{aligned} d\Lambda_B^{(A)}(p) &= d\Lambda_B(p)\mathbb{P}_B^{(A)}(p) = d\Lambda_B(p)\sum_{l=l^*}^L v_l \\ \Rightarrow \Lambda_B^{(A)}(p) &= \sum_{l=0}^{l^*-1} v_l \Lambda_B(p_l^{(\text{cov})}) + \sum_{l=l^*}^L v_l \Lambda_B(p) \end{aligned} \quad (14)$$

with l^* depending on p as in Eq. (12) and $\Lambda_B(p) = \lambda_B \Upsilon p^{\frac{2}{\alpha}}$.

Proof: This Lemma directly follows from the thinning property of PPPs and from [31, Prop.1.3.5]. \square

This expression of $\Lambda_B^{(A)}$ can be interpreted as follows. Any scBS for which the transmit power required by MT⁽⁰⁾ is equal to $p \in [0, p_{l^*}^{(\text{cov})}]$ is declared available if the power buffer state is greater than l^* . This gives the term $\Lambda_B(p)\sum_{l=l^*}^L v_l$. However, any scBS for which $p \in [0, p_{l^*-1}^{(\text{cov})}]$ can be declared also available if the power buffer is in state $l^* - 1$. This gives the additional term $v_{l^*-1} \Lambda_B(p_{l^*-1}^{(\text{cov})})$, etc.

B. Probability to be Associated With the Typical scBS

By Definition 2, the probability $\mathbb{P}_B^{(\text{Ass})}(p|l)$ that a MT requiring a power p is associated with the typical small-cell base station sc-BS⁽⁰⁾, given that l power units are available in its battery, is equal to the probability that scBS⁽⁰⁾ is the ‘‘closest’’ available base station in terms of transmit power p . With $\Lambda_B^{(A)}(p)$ the density of available scBSs, it follows from the void probability of PPPs that

$$\mathbb{P}_B^{(\text{Ass})}(p|l) = \begin{cases} \exp(-\Lambda_B^{(A)}(p)) & p \leq p_l^{(\text{cov})} \\ 0 & \text{otherwise} \end{cases} \quad (15)$$

VI. ANALYSIS OF THE PROPOSED CELL ASSOCIATION: THE BS'S PERSPECTIVE

This section switches to the perspective of a BS and characterizes the set of served MTs and the battery state.

A. A Useful Theorem: Sum of Transmit Power

Before moving onto the analysis of the proposed cell association, we propose a general and useful theorem:

Theorem 1: Assume that the set of the transmit powers p_{0j} from the typical base station scBS⁽⁰⁾ to its served MTs form a PPP denoted as Φ and of density $\Lambda(p)$. In addition, assume that $p_{0j} \leq P \in \mathbb{N}, \forall j$. Then, the probability of the

discretized total power consumption at scBS⁽⁰⁾ denoted as $\mathbb{P}_\Sigma(m, \Lambda, P) = \mathbb{P}\left(\sum_{j \in \Phi} \lceil p_{kj} \rceil = m\right)$ is found recursively:

$$\begin{cases} \mathbb{P}_\Sigma(0, \Lambda, P) = \exp(-\Lambda(P)) \\ \mathbb{P}_\Sigma(m, \Lambda, P) = \sum_{q=1}^{m^*} \frac{q}{m} C_q \mathbb{P}_\Sigma(m-q, \Lambda, P) \end{cases}$$

where $C_q = \Lambda(q) - \Lambda(q-1)$ and $m^* = \min(m, P)$.

Proof: See Appendix B. \square

In Theorem 1, C_q refers to the average number of MTs requiring exactly q units of energy for data transmission (after rounding up). The probability $\mathbb{P}_\Sigma(0, \Lambda, P)$ that the scBS does not consume energy at all is equal to the probability that there is no MT satisfying $p_{0j} < P$.

Remark: This theorem has wide application and allows to compute the transmit power of a multi-user transmission where power is minimized given path-loss and shadowing. It is used in this work to analyze the set of served MTs and the interference received at MTs.

B. Analysis of the set of Served MTs

As described in Definition 3, the typical base station scBS⁽⁰⁾ selects MTs in increasing order of required transmit power based on the *effective* set of associated MTs, while cell association is performed by MTs based on an *estimate* set of associated MTs (which depends on the estimate power $\tilde{P}_{0 \setminus j}^{(T)} \forall j$). As a consequence, there exists a non-zero probability that a MT associated with a scBS cannot be effectively served due to power shortage. A MT _{j} requiring a transmit power of p_{0j} is rejected by scBS⁽⁰⁾ if the current realization of the PPP network and channel gains leads to $p_{0j} + \sum_{i \in \mathcal{S}_{0 \setminus j}} \lceil p_{0i} \rceil > P_0^{(A)}$, i.e. if $\tilde{P}_{0 \setminus j}^{(T)}$ has been underestimated. However, the rejection probability is negligible and we propose the following approximation, valid only for the proposed scheme.

Approximation 1: The subset \mathcal{S}_0 of MTs served by the typical small-cell base station scBS⁽⁰⁾ is approximated by the subset of MTs associated to it.

Such approximation upper-bounds the set of served MTs and states that the proposed cell association guarantees service to any associated MT.

Lemma 2: Given that l power units are available in the battery, the subset \mathcal{S}_0 of MTs served by scBS⁽⁰⁾ forms a PPP on $[0, p_l^{(\text{cov})}]$, with:

$$\begin{aligned} d\Lambda_{MT}^{(S)}(p | l) &= d\Lambda_{MT}(p)\mathbb{P}_B^{(\text{Ass})}(p|l) \\ &= \lambda_{MT} \frac{2}{\alpha} \Upsilon p^{\frac{2}{\alpha}-1} \exp(-\Lambda_B^{(A)}(p)) \end{aligned} \quad (17)$$

The closed-form expression of $\Lambda_{MT}^{(S)}(p|l)$ is computed by integration, as in Eq. (16), at the bottom of next page.

C. Characterization of the Battery State Probability Vector

As $\Lambda_{MT}^{(S)}(p | l)$ refers to the density of \mathcal{S}_0 given that there are l power units in the battery, i.e. the subset of MTs served by scBS⁽⁰⁾ at time slot t , we apply Theorem 1 to compute the

TABLE II
FIXED-POINT METHOD TO OBTAIN $\mathbf{v} = [v_0 v_1 \dots v_L]$

1: $v_l = \frac{1}{L+1} \quad \forall l$	% Equiprobable states
2: $\Delta = 1 > \delta$	% Stopping condition, $\delta = 10^{-10}$ here
3: Compute $\mathbb{P}_H(m)$ as in Eq. (6)	
4: while $\Delta > \delta$ do	
5: Compute $\Lambda_B^{(A)}(p)$ using Eq. (14)	
6: Compute $\Lambda_{MT}^{(S)}(p l)$ using Eq. (16)	
7: Compute $\mathbb{P}_T(m l)$ as in Eq. (18)	
8: Compute $\mathbf{P} = [\mathbb{P}_{lq}^{\rightarrow}]$ as in Eq. (19)	
9: $\Delta = \mathbb{E}[(\mathbf{v} - \mathbf{vP})^2]$	% Mean squared error
10: $\mathbf{v} = \mathbf{vP}$, ensuring $\sum_l v_l = 1$	
11: end while	
12: return \mathbf{v}	

total power consumption as follows:

$$\mathbb{P}_T(m | l) = \begin{cases} \frac{\mathbb{P}_\Sigma(m, \Lambda_{MT}^{(S)}(p | l), \lfloor p_l^{(\text{cov})} \rfloor)}{\mathbb{P}_{\text{sum}}(l)} & \text{if } m \leq l \\ 0 & \text{otherwise.} \end{cases}$$

$$\text{where } \mathbb{P}_{\text{sum}}(l) = \sum_{m=1}^l \mathbb{P}_\Sigma(m, \Lambda_{MT}^{(S)}(p | l), \lfloor p_l^{(\text{cov})} \rfloor) \quad (18)$$

and $p_l^{(\text{cov})}$ refers to the maximum transmit power that can be required by a MT of \mathcal{S}_0 , as given in Eq. (11). Next, we compute the matrix \mathbf{P} . Given the battery model described in Subsection III-D, the probability to go from state l to state q from a time slot to the next one is given by:

$$\forall l \begin{cases} \mathbb{P}_{lq}^{\rightarrow} = \sum_m \mathbb{P}_T(m | l) \mathbb{P}_H(q - l + m) \forall q \neq L \\ \mathbb{P}_{lL}^{\rightarrow} = \sum_m \mathbb{P}_T(m | l) \sum_{q \geq L-l+m} \mathbb{P}_H(q) \end{cases} \quad (19)$$

The case $q = L$ accounts for the finite battery capacity: no more than L power units can be stored, whatever the amount of harvested power.

Finally, we propose to numerically solve the steady-state system of Eq. (9) and obtain \mathbf{v} by applying the algorithm in Table II. This algorithm is directly inspired from the fixed-point method commonly used to solve systems of the form $x = f(x)$. If $\mathbf{v}^{(0)}$ represents a first guess for the solution, successive approximations to the solution are computed as $\mathbf{v}^{(n+1)} = \mathbf{v}^{(n)}\mathbf{P}$. Following the Doeblin's theorem for Markov chains, such an algorithm is known to converge to the stationary distribution for all initial distributions. In our case, it converges after 10 to 20 iterations only.

VII. PERFORMANCE OF THE PROPOSED ASSOCIATION

We now analyze the performance achieved by the proposed energy-aware cell association.

A. Probability of Power Outage

A power outage occurs either when a MT cannot find any available scBS or when it is associated but dropped due to power shortage. With regards to the proposed association, this second event can be neglected. As highlighted in Approx. 1, MTs have low probability to be dropped once associated.

Proposition 1: The probability of power outage $\mathbb{P}_{\text{out}}^{(A)}$ of the proposed cell association is expressed as

$$\mathbb{P}_{\text{out}}^{(A)} = \exp\left(-\Lambda_B^{(A)}\left(p_L^{(\text{cov})}\right)\right)$$

where $\Lambda_B^{(A)}$ is defined in Eq. (14) and $p_L^{(\text{cov})}$ is the maximal power that can be required by a MT, solving Eq.(11).

Proof: First, given that BSs cannot store more than L power units, the maximum power that can be required by a MT is equal to $p_L^{(\text{cov})}$, regardless of the current BS battery state. Thus, any BS_k for which $p_{k0} > p_L^{(\text{cov})}$ is declared non-available. Second, not all BSs for which the required transmit power satisfies $p_{k0} \leq p_L^{(\text{cov})}$ is available, since they may lack of power. Accounting for the random battery fluctuations, their density is reduced from Λ_B to $\Lambda_B^{(A)}$. Finally, using the void probability of PPPs [31], we deduce Proposition 1. \square

B. Coverage Probability

The coverage probability \mathbb{P}_γ is defined as the probability that the signal-to-interference ratio (SIR) at $\text{MT}^{(0)}$ exceeds a given reliability threshold T . While the availability criteria and power outage probability only depend on path-loss and shadowing, this performance metric accounts for fast fading and interference as well.

We denote as N_{RB} the number of resource blocks available for data transmission at each small-cell BS. They are assumed picked at random, each with equal probability $\frac{1}{N_{RB}}$. First, the expected transmit power of scBS_k , $\forall k$ in the resource block used by $\text{MT}^{(0)}$ is equal to $\frac{\mathbf{P}_k^{(T)}}{N_{RB}}$, with $\mathbf{P}_k^{(T)}$ the total transmit power of scBS_k . Denoting scBS_0 the small base station serving $\text{MT}^{(0)}$, the interference I received at $\text{MT}^{(0)}$ is computed as:

$$I = \sum_{\text{scBS}_k \in \Phi_B \setminus \text{scBS}_0} \frac{\mathbf{P}_k^{(T)}}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2$$

$$= \sum_{m=1}^L \sum_{l=m}^L \sum_{\Phi_{m,l}^{(l)}} \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2, \quad (20)$$

where m refers a total transmit power, l to a BS battery state and $\Phi_{m,l}^{(l)}$ refers to the set of interfering scBSs having l units of energy stored in their battery and transmitting with $m \leq l$ power units. Note that the $\Phi_{m,l}^{(l)}$ form a partition of the interfering scBSs, as $\Phi_B \setminus \text{scBS}_0 = \bigcup_{m=0}^L \bigcup_{l=m}^L \Phi_{m,l}^{(l)}$.

$$\Lambda_{MT}^{(S)}(0 | l) = 0 \quad \text{and} \quad \Lambda_{MT}^{(S)}(p | l) = \Lambda_{MT}^{(S)}(p_{l^*-1}^{(\text{cov})} | l) + \frac{\lambda_{MT}}{\lambda_B} \frac{1}{\sum_{l=l^*}^L v_l} \left[\exp\left(-\Lambda_B^{(A)}(p_{l^*-1}^{(\text{cov})})\right) - \exp\left(-\Lambda_B^{(A)}(p)\right) \right] \quad (16)$$

Proposition 2: The coverage probability of the proposed cell association is given by:

$$\mathbb{P}_\gamma^{(A)} = \prod_{m=1}^L \prod_{l=m}^L \exp\left(-\rho_{m,l} \Upsilon_m \int_{u_{m,l}}^{\infty} \frac{u^{2/\alpha-1}}{1+u} du\right)$$

$$\text{with } \begin{cases} \Upsilon_m &= \pi \left(\frac{m}{\kappa N_{RB}}\right)^{\frac{2}{\alpha}} \exp\left(\frac{2/\alpha}{\zeta} \mu + \frac{1}{2} \left(\frac{2/\alpha}{\zeta}\right)^2 \sigma^2\right) \\ \rho_{m,l} &= v_l \mathbb{P}_T(m | l) \lambda_B \frac{2}{\alpha} \left(\frac{T}{P_{Rx}}\right)^{\frac{2}{\alpha}} \\ u_{m,l} &= \min\left(\frac{1}{T}, \frac{p_l^{(\text{cov})} N_{RB}}{mT}\right) \end{cases}$$

In this, $v_l \mathbb{P}_T(m | l) \lambda_B$ refers to the density of $\Phi_{m,l}^{(I)}$ and $\mathbb{P}_T(m | l)$ is given by Eq. (18), using Theorem 1.

Proof: See Appendix C. \square

Such expression of the coverage probability is derived from the Laplace transform of the received interference in PPP networks. This stochastic-geometry tool has been widely used in conventional cellular networks with fixed transmit power, as in [32]. In our case, the BS transmit power is not constant but partitioning the BSs into the sets $\Phi_{m,l}^{(I)}$ allows to consider a fixed average transmit power equal to $\frac{m}{N_{RB}}$ for analyzing the received interference. Another difference with existing frameworks dedicated to non energy-harvesting networks lies in the power received from the closest interfering scBS, measured by $\frac{P_{Rx}}{u_{m,l} T}$. Whereas an interferer cannot be closer than r_0 (users associate with the strongest BS), it is not the case in our framework due to the availability criteria. Indeed, a nearby BS may be declared unavailable for a given user, which then has to associate with a farther BS.

Remark: Theorem 1 allows to discard the assumption of full-power transmission with saturated traffic load in the computation of the received interference, as commonly used for tractable analysis [18], [20]. With our scenario and considered network model, such assumption would imply that the transmit power model for the battery discharge (which accounts for the potentially low number of served MTs) does not match the transmit power model for the received interference (which gives a worst-case result for the coverage probability). In the proposed analysis, the effective inter-cell interference is computed based on the battery level and power requirements of associated MTs. Thus, a scBS with low battery level and serving few MTs also generates less interference.

VIII. SIMULATIONS AND PERFORMANCE RESULTS

We first validate the proposed analysis and then, present the performance obtained for the energy-aware cell association, with a particular focus on the power outage.

A. Considered Reference Cell Association Strategies

In the following, the proposed cell association is referred as “ \mathcal{A} ”. As first reference, we consider the performance achieved when scBSs are connected to the power grid and do not require energy harvesting. As for the proposed strategy, we assume that the transmit power is minimized and that users associate with the scBS consuming the least power.

A maximum transmit power constraint $P_{\max}^{(\text{OG})}$ is assumed for data transmission towards each user. Such scheme is referred as “*on-grid*” and gives performance upper bound.

As second reference scheme, we consider a more conventional association policy with energy harvesting but without power availability checking. Similarly to \mathcal{A} , a MT associates to the scBS for which the required transmit power is minimal, as in Definition 2, but the battery level is not considered and no pre-selection of available base stations is performed. In this case, $\mathcal{A}_j = \Phi_B$ for all j . This scheme is referred as “*w/o \mathcal{A}* ”.

As third reference, we consider a cell association policy similar to the proposed one, with power availability criteria and minimal-power association, but where the BSI (battery state information) can be known in real-time, at any instant. In this case, a MT performs cell association knowing the effective instantaneous battery level of each small-cell base station. The power availability criteria is thus reduced to $p_{kj} \leq P_k^{(A)}$ and, contrary to the proposed strategy, MTs are served in a first-come first-served basis and not in ascending order of required power, as no non-causal information is assumed. Such scheme is denoted as “*rt- \mathcal{A}* ”.

Remark: Performance upper-bounds can be obtained by considering centralized cell association, where the scBS-MT pairing is computed at each instant with global instantaneous knowledge of channel and battery states. Yet, such optimized algorithms require large amount of overhead signaling. The resulting extra power consumption may rapidly depletes the BS battery but is generally omitted for performance analysis. Computing the optimal solution within the considered framework and proposing an optimal/suboptimal algorithm for it largely exceeds the scope of this paper.

B. Simulation Setup and Analysis Validation

To simulate the network performance and validate the proposed analysis, we use Monte-Carlo simulations. Each simulation trial first consists in generating the base station PPP in a finite window. The battery level at each BS is initially set as random, taken from a uniform distribution. Then, a sufficiently large number of sub-trials is simulated to model the BSI broadcast periods. Each of them consists in generating the energy arrivals at each scBS and the user PPP in the considered window. Next, cell association is performed, the battery level is updated following the effective harvested and consumed energy and both outage and coverage are evaluated for this sub-trial. Note that, to avoid any result distortion due to the initial conditions, a transition period is simulated at the beginning of each trial such that each battery reaches its stationary state. Finally, the outage and coverage probabilities are computed by averaging over 10,000 such trials. If not specified, we consider the parameters of Table III.

Before moving onto performance results, we validate the analysis proposed in this paper. The outage and coverage probabilities obtained by Monte-Carlo simulations are depicted in Figures 5, 6 and 8 for a wide range of simulation parameters. The plots show a complete agreement between the analytical and simulated results. In particular, Figures 5 and 6 depict both the simulated probability that MT_0 cannot associate with any

TABLE III
DEFAULT SIMULATION PARAMETERS

Channel		scBS		MT	
κ / α	1 / 4	λ_{BS}	$\frac{1}{\pi 60^2}$	λ_{MT}	$\frac{15}{\pi 60^2}$
μ / σ	0 / 4dB	L / P _{max}	1000 / 1W	P _{Rx}	-65dBm
ν	1	λ_e / N_e	10%L / 1	P _{max} ^(OG)	50mW

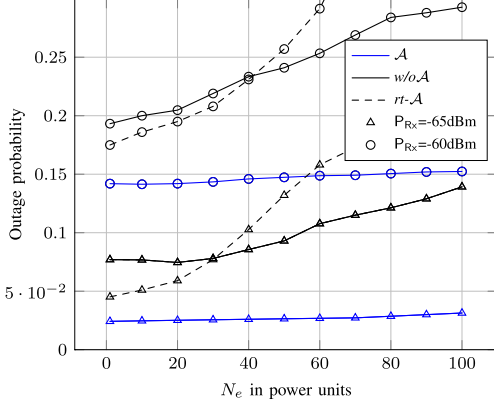


Fig. 4. Impact of the burstiness of energy arrivals on the power outage.

scBS (namely, “simul. $1 - \mathbb{P}_B^{(Ass)}$ ”, in the Figure) and the effective simulated power outage probability (namely, “simul. $\mathbb{P}_{out}^{(A)}$ ”), which also includes the cases when MT₀ is associated with a scBS but not selected for service. The good match of both of them with the power outage as computed in Proposition 1 validates the proposed analysis and Approximation 1.

C. Performance Gain Reached by the Novel Association

1) *Robustness to Bursty Energy Arrivals:* Along with its uncertainty, the energy arrival process is characterized by its irregularity. As first part of the simulation results, we evaluate the robustness of the proposed association against bursty arrivals. To do so, we consider that energy is harvested at rate $\frac{\lambda_e}{N_e}$ over one time slot and that each arrival consists of $N_e \tau$ energy units. When N_e increases, energy is harvested less frequently, but each burst carries more power units.

The outage probabilities obtained for schemes \mathcal{A} , $w/o\text{-}\mathcal{A}$ and $rt\text{-}\mathcal{A}$ are illustrated in Figure 4. Significant loss in the power outage is observed for both $w/o\text{-}\mathcal{A}$ and $rt\text{-}\mathcal{A}$ when harvesting is bursty (high values for N_e). As no energy management is performed and users associate with scBSs ignoring their battery level, $w/o\text{-}\mathcal{A}$ is severely handicapped by long periods without energy arrivals. In addition, more energy is wasted due to battery overflow at scBSs serving few users. Next, the performance of $rt\text{-}\mathcal{A}$ is essentially conditioned by the arrival order of the power bursts and MTs service requests (first-come first-served approach). Receiving large power bursts allows serving users at cell edge or with weak channel, i.e. users with high power requirement, but this rapidly depletes the battery and prevents from serving other users at next time slot.

On the contrary, the proposed power availability criteria is only slightly affected by the burstiness of the

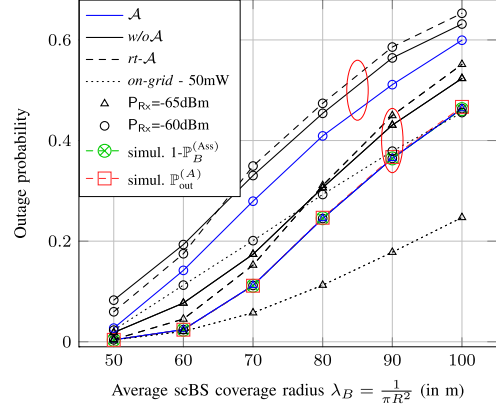


Fig. 5. Impact of the scBS density on the power outage.

energy arrival process. Such gain is further illustrated in Figures 3(b) and (c). As traffic is offloaded from scBSs with low battery to scBSs with higher battery and users are served in ascending order of power requirement, the overall available energy is more evenly distributed among base stations to serve users. Thus, following principles enunciated in [33], the proposed availability checking can be considered as a non-direct energy-sharing mechanism within wireless networks, in the same way as node cooperation.

Remark: As observed in Figure 4, the case $N_e = 1$ (regular energy arrivals) presents the minimal gain of the proposed cell association over both $w/o\text{-}\mathcal{A}$ and $rt\text{-}\mathcal{A}$. As it constitutes a lower-bound on the achievable performance gain, it is the only case considered in the following.

2) *Impact of the BS Density:* The impact of the scBS density on the probability of power outage is depicted in Figure 5. Comparing the proposed cell association with $w/o\text{-}\mathcal{A}$, we observe that the power availability checking provides a relatively constant gain, which increases when the received power constraint P_{Rx} decreases. Indeed, with smaller P_{Rx} , a user requires less transmit power and can generally associate with more BSs, even if located farther. Hence, a smoother distribution of the available energy can be reached among the scBSs in the network, by non-direct energy sharing. By comparison with the *on-grid* strategy, the outage loss due to energy harvesting is deeper for large cells. The considered association strategies with energy-harvesting BS are limited in their total power consumption by the battery and cannot serve far users due to power shortage, while we assume for the *on-grid* strategy a transmit power constraint at each user only, and not on the overall consumption.

3) *Received Power Constraint and Harvesting Rate:* In Figure 6, the power outage probability is plotted as a function of the received power constraint P_{Rx} . As observed, the proposed energy-aware scheme outperforms both $w/o\text{-}\mathcal{A}$ and $rt\text{-}\mathcal{A}$ and approaches the performance of the *on-grid* policy for $P_{max}^{(OG)} = 50\text{mW}$. Furthermore, the gain increases when the harvesting rate λ_e diminishes. This suggests that the power availability checking of Def. 1 brings robustness to impaired harvesting conditions, e.g. cloudy days for solar

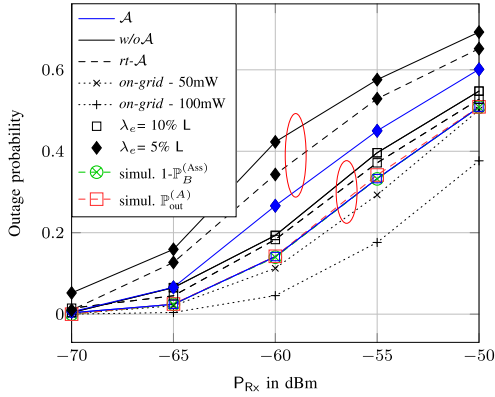


Fig. 6. Impact of the required received power constraint P_{R_X} .

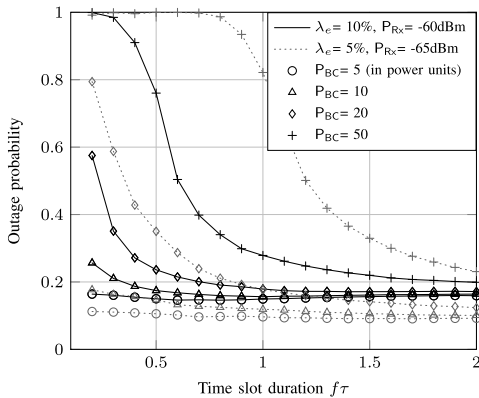


Fig. 7. BS battery broadcast: dissipated power and frequency of broadcast.

photovoltaic panels. We also recall that such results have been obtained for $N_e = 1$, which lower-bounds the gain of the proposed strategy.

4) *On the Frequency of Battery Broadcast:* So far, we have omitted the power P_{BC} that is consumed by each scBS to periodically broadcast its battery level. To analyze its impact on the power outage probability, we now assume that the time slot duration τ is scaled by a factor $f \in [0.1, 2]$. We adapt the algorithm proposed in Table II to this new assumption by limiting the battery capacity to $P_{\max} - P_{BC}$ and setting the density of users (resp. of power arrivals) to $\lambda_{MT} f$ (resp. $\lambda_e f$), following the properties of Poisson processes.

As observed in Fig. 7, the power P_{BC} dissipated at each time slot significantly impairs the outage probability when the time slot duration is short ($f \leq 0.75$). Indeed, the harvested power units are mostly consumed for battery broadcasting, letting little power available for data transmission. However, and quite counter-intuitively, the outage probability tends to a fixed value when f increases. The impact of P_{BC} is then negligible and the performance is solely affected by the ratio between $\lambda_e f$ and $\lambda_{MT} f$, which is constant in our case. This implies that (i) the battery broadcasts can be spaced out as long as the Poisson assumption for power unit arrivals and number of MTs is valid over the time slot and (ii) that the time slot duration should be set based on the traffic variations and harvesting conditions. Stable traffic demand and slowly varying weather conditions

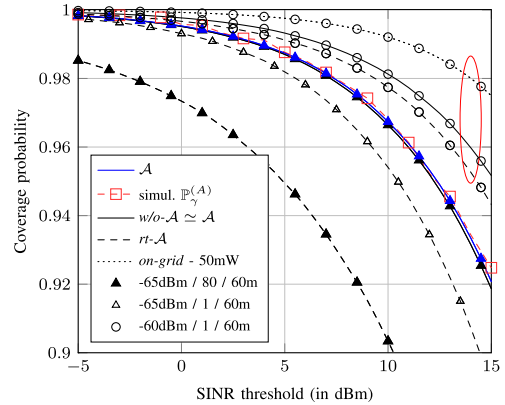


Fig. 8. Coverage probability (legend: $P_{R_X} / N_e / R$).

(e.g. for solar panels) allows significant reduction in the battery broadcasting frequency.

5) *On the Coverage Probability:* Finally, we observed from Figure 8 that the proposed strategy does not lead to noticeable reduction in the coverage probability compared to $w/o-A$, although it allows to serve more users (This is plotted for the case $P_{R_X} = -65\text{dBm} / N_e = 80 / R = 60\text{m}$ only, for more readability). Even though a MT may associate to a farther scBS by applying the power availability checking, the resulting additional transmit power at the serving BS is not high enough to affect the interference received at users of other cells. Another important outcome that can be derived from this figure regards the user selection strategy. While for both $w/o-A$ and A , users are selected in ascending order of power requirement, the $rt-A$ is based on a first-come first served approach. It follows that a user with very high power requirement, for example due to weak channel state, will be served as soon as sufficient energy is available, hence generating high interference for other users. This is particularly detrimental for bursty energy arrivals ($N_e = 80$).

IX. CONCLUSION

We have proposed a novel user association strategy for small-cell networks constrained by energy harvesting. It takes advantages from (i) a BS power availability checking prior to effective association, (ii) transmit power minimization, to satisfy a received power constraint and (iii) user selection at BSs in ascending order of the power requirement. The proposed strategy only necessitates periodical broadcast of the BS battery level and accommodates the power consumed to transmit data to all users potentially associated to the same BS. Then, we have proposed for it a comprehensive analysis which jointly captures the effect of the battery fluctuations and the users power requirement. Simulations show that the proposed scheme significantly outperforms conventional ones. By efficiently offloading traffic at BSs with low battery, the proposed association allows a more even distribution of the available energy in the network and acts as a non-direct energy-sharing mechanism. In addition, it is more robust to energy harvesting impairment and BS density reduction.

APPENDIX A
PROOF OF EQ. 7

From the displacement theorem as used in [34, Lemma 1],

$$\begin{aligned}\Lambda_{MT}(p) &= \lambda_{MT} \int_{\mathbb{R}^+} \mathbb{P}\left(\mathbb{P}_{\text{Rx}} \frac{l(r)}{\chi_{0j}} \in [0, p)\right) dr \\ &= \lambda_{MT} \mathbb{E}_\chi \left[\pi \left(\frac{p\chi_{0j}}{\kappa \mathbb{P}_{\text{Rx}}} \right)^{\frac{2}{\alpha}} \right] = \lambda_{MT} \pi \left(\frac{p}{\kappa \mathbb{P}_{\text{Rx}}} \right)^{\frac{2}{\alpha}} \mathbb{E} \left[\chi_{0j}^{\frac{2}{\alpha}} \right]\end{aligned}$$

The last line comes from the independence of the shadowing attenuation on each scBS-MT link and $\mathbb{E} \left[\chi_{0j}^{\frac{2}{\alpha}} \right]$ is the fractional moment of a log-normal RV. With $\zeta = 10/\ln(10)$, $\mathbb{E} \left[\chi_{0j}^{\frac{2}{\alpha}} \right] = \exp \left(\frac{2/\alpha}{\zeta} \mu + \frac{1}{2} \left(\frac{2/\alpha}{\zeta} \right)^2 \sigma^2 \right) = \Upsilon_\chi$. Then, the estimate total power consumption $\tilde{\mathbb{P}}_{k \setminus 0}^{(T)}$ is computed using the Campbell's theorem as follows:

$$\tilde{\mathbb{P}}_{k \setminus 0}^{(T)} = \int_0^{p_{k0}} p d\Lambda_{MT}(p) dp = \lambda_{MT} \Upsilon \frac{2/\alpha}{2/\alpha + 1} (p_{k0})^{\frac{2}{\alpha} + 1}.$$

APPENDIX B
PROOF OF THEOREM 1

Let's consider the probability generating function of total power consumption $\Sigma = \sum_{j \in \Phi} \lceil p_{kj} \rceil$:

$$G_\Sigma(t) = \mathbb{E}(t^\Sigma) = \sum_{m=0}^{\infty} t^m \mathbb{P}(\Sigma = m)$$

such that $\forall m, \mathbb{P}(\Sigma = m) = \frac{1}{m!} \frac{d^m G_\Sigma}{dt^m}(0)$.

As the MTs served by the typical base station scBS⁽⁰⁾ form a PPP of density $\Lambda(p)$, we have with $j \in \Phi \cap [0, P[$:

$$\begin{aligned}G_\Sigma(t) &= \mathbb{E} \left(t^{\left(\sum_j \lceil p_{0j} \rceil \right)} \right) = \mathbb{E} \left(\prod_j t^{\lceil p_{0j} \rceil} \right) \\ &= \exp \left(- \int_0^P (1 - t^{\lceil p \rceil}) d\Lambda(p) dp \right) \\ &= \exp \left(- \sum_{q=1}^P (1 - t^q) \int_{q-1}^q d\Lambda(p) dp \right)\end{aligned}$$

Let's denote $C_q = \int_{q-1}^q d\Lambda(p) dp$. Then, by induction, we get:

$$\begin{aligned}(0) \quad & \begin{cases} G_\Sigma(t) = \exp \left(\sum_{q=1}^P C_q (t^q - 1) \right) \\ G_\Sigma(0) = \exp \left(- \sum_{q=1}^P C_q \right) \end{cases} \\ (1) \quad & \begin{cases} \frac{dG_\Sigma}{dt}(t) = \left(\sum_{q=1}^P C_q q t^{q-1} \right) G_\Sigma(t) \\ \frac{dG_\Sigma}{dt}(0) = C_1 G_\Sigma(0) \end{cases} \\ (2) \quad & \begin{cases} \frac{d^2 G_\Sigma}{dt^2}(t) = \left(\sum_{q=1}^P C_q q t^{q-1} \right) \frac{dG_\Sigma}{dt}(t) \\ \quad + \left(\sum_{q=2}^P C_q q(q-1) t^{q-2} \right) G_\Sigma(t) \\ \frac{d^2 G_\Sigma}{dt^2}(0) = C_2 G_\Sigma(0) + C_1 \frac{dG_\Sigma}{dt}(0) \end{cases}\end{aligned}$$

which leads to $\frac{d^m G_\Sigma}{dt^m}(0) = \sum_{q=1}^{m^*} \binom{m-1}{q-1} C_q q! \frac{d^{m-q} G_\Sigma}{dt^{m-q}}(0)$ and completes the proof.

APPENDIX C
PROOF OF PROPOSITION 2

We first focus on the coverage probability. We have:

$$\begin{aligned}\mathbb{P}_y &= \mathbb{P} \left(\frac{\mathbb{P}_{\text{Rx}} |h_{1,0}|^2}{I} \geq T \right) \\ &= \mathbb{E} \left[\mathbb{P}_h \left(|h_{1,0}|^2 \geq \frac{T}{\mathbb{P}_{\text{Rx}}} \sum_{m=1}^L \sum_{l=m}^L \sum_{\Phi_{m,l}^{(l)}} \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2 \right) \right] \\ &= \mathbb{E} \left[\exp \left(- \sum_{m=1}^L \sum_{l=m}^L \sum_{\Phi_{m,l}^{(l)}} \nu \frac{T}{\mathbb{P}_{\text{Rx}}} \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2 \right) \right] \\ &= \prod_{m=1}^L \prod_{l=m}^L \mathbb{E} \left[\exp \left(- \sum_{\Phi_{m,l}^{(l)}} \nu \frac{T}{\mathbb{P}_{\text{Rx}}} \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2 \right) \right] \\ &= \prod_{m=1}^L \prod_{l=m}^L \mathcal{L}_{m,l} \left(\nu \frac{T}{\mathbb{P}_{\text{Rx}}} \right)\end{aligned}$$

The Laplace transform of the total interference received from scBSs in $\Phi_{m,l}^{(l)}$ is given by

$$\begin{aligned}\mathcal{L}_{m,l}(s) &= \mathbb{E} \left[\prod_{\Phi_{m,l}^{(l)}} \exp \left(-s \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2 \right) \right] \\ &= \mathbb{E}_{\Phi_{m,l}^{(l)}} \left[\prod_{\Phi_{m,l}^{(l)}} \mathbb{E}_h \left[\exp \left(-s \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})} |h_{k,0}|^2 \right) \right] \right] \\ &= \mathbb{E}_{\Phi_{m,l}^{(l)}} \left[\prod_{\Phi_{m,l}^{(l)}} \frac{\nu}{\nu + s \frac{m}{N_{RB}} \frac{\chi_{k,0}}{l(r_{k,0})}} \right]\end{aligned}$$

Let's denote $z_k = \frac{N_{RB}}{m} \frac{l(r_{k,0})}{\chi_{k,0}} = \frac{N_{RB}}{m \mathbb{P}_{\text{Rx}}} p_{k0}, \forall k$, which refers to the inverse of the power received from the interfering scBS_k. The set of z_k thus forms a displaced PPP of $\Phi_{m,l}^{(l)}$. Its intensity is computed using a proof similar to Appendix A as follows:

$$\Lambda_{m,l}^{(l)}(z) = \nu_l \mathbb{P}_T(m | l) \lambda_B \Upsilon_m z^{\frac{2}{\alpha}}$$

where Υ_m are as in Proposition 2. In addition, let's consider scBS_j the closest interfering base station of $\Phi_{m,l}^{(l)}$ (closest in terms of both path-loss and shadowing). If scBS_j is available for the typical user MT₀, we know for sure that $z_j > \frac{1}{\mathbb{P}_{\text{Rx}}}$.

The availability criteria also implies that $z_j < \frac{N_{RB}}{m \mathbb{P}_{\text{Rx}}} p_l^{(\text{cov})}$.

If scBS_j is not available for MT₀, then $z_j > \frac{N_{RB}}{m \mathbb{P}_{\text{Rx}}} p_l^{(\text{cov})}$.

Defining $z_{m,l} = \min \left(\frac{1}{\mathbb{P}_{\text{Rx}}}, \frac{N_{RB}}{m \mathbb{P}_{\text{Rx}}} p_l^{(\text{cov})} \right)$ and $u = \frac{\nu}{s} z$, we get:

$$\begin{aligned}\mathcal{L}_{m,l}(s) &= \mathbb{E}_{\Phi_{m,l}^{(l)}} \left[\prod_{\Phi_{m,l}^{(l)}} \frac{\nu}{\nu + s/z_k} \right] \\ &= \exp \left(- \int_{z_{m,l}}^{\infty} \left(1 - \frac{\nu}{\nu + s/z} \right) d\Lambda_{m,l}^{(l)}(z) dz \right) \\ &= \exp \left(- \rho_{m,l} \lambda_B \Upsilon_m \frac{2}{\alpha} \left(\frac{s}{\nu} \right)^{\frac{2}{\alpha}} \int_{u_{m,l}}^{\infty} \frac{u^{\frac{2}{\alpha}-1}}{1+u} du \right)\end{aligned}$$

which concludes the proof.

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Fanny Parzys (S'11–M'15) received the Ph.D. degree from the École de Technologie Supérieure, Montreal, Canada, in 2015, and the M.Sc. degree from Telecom ParisTech, France, in 2009. She was a Post-Doctoral Researcher with the Universitat de Barcelona, Spain, within the Marie Skłodowska-Curie Program. She is currently with the Wireless Communications Research Group (WiCom), Universitat Pompeu Fabra, Barcelona, Spain, as a Post-Doctoral Fellow. Her interest covers various aspects of wireless communication and network performance modeling using stochastic geometry tools.



Marco Di Renzo (S'05–AM'07–M'09–SM'14) received the Laurea (*cum laude*) and Ph.D. degrees in electrical engineering from the University of L'Aquila, Italy, in 2003 and 2007, respectively, and the D.Sc. degree from Université Paris-Saclay, France, in 2013. He has held research and academic positions with the University of L'Aquila, Italy, Virginia Tech, USA, CTTC, Spain, and The University of Edinburgh, U.K. Since 2010, he has been a CNRS Associate Professor with the Laboratory of Signals and Systems, Paris-Saclay University-CNRS, Centrale Supélec, Université Paris-Sud, Paris, France. He is a recipient of several research distinctions and best paper awards. He currently serves as an Editor of the IEEE COMMUNICATION LETTERS and the IEEE TRANSACTION ON COMMUNICATIONS, and is the Editor for Heterogeneous Networks Modeling and Analysis of the IEEE Communications Society.



Christos Verikoukis received the Ph.D. degree from the Technical University of Catalonia in 2000. He is currently a Fellow Researcher with CTTC and an Adjunct Professor with the Universitat de Barcelona, Spain. He has published 106 journal papers and over 170 conference papers. He is also a co-author of three books, 16 chapters in different books, and two patents. He was a recipient of several Best Paper Awards and is currently the Chair of the IEEE ComSoc Technical Committee on Communication Systems Integration and Modeling.