A Novel Performance Tradeoff in Heterogeneous Networks: A Multi-Objective Approach

Mohammad Robat Mili, Ata Khalili, *Student Member, IEEE*, Derrick Wing Kwan Ng, *Senior Member, IEEE*, and Heidi Steendam, *Senior Member, IEEE*

***Abstract*—In this letter, we investigate the performance tradeoff between different tiers of heterogeneous networks (HetNets) consisting of a macrocell as the basic tier and small cells (e.g., picocells, femtocells, etc.) as the other tiers. Due to the interference among tiers in the HetNets, the performance of different cells are interactive. Maximizing the total performance in terms of data rate and energy efficiency (EE) of users in HetNets are both desirable system design objectives, however, it is expected that there is a non-trivial tradeoff between tiers due to the co-channel deployment. Thus, we formulate our resource allocation problem as a multiobjective optimization problem (MOOP) in which the performance of the macrocell and small cells are jointly maximized. Using the weighted Tchebycheff technique, we are able to transform the MOOP into a single objective optimization problem (SOOP). Then, an iterative algorithm is proposed to solve this SOOP which yields a locally optimal solution. Finally, our numerical results show this tradeoff among different tiers.**

***Index Terms*—Heterogeneous networks, multiobjective optimization, performance tradeoff.**

I. Introduction

HETEROGENEOUS networks (HetNets) are recently considered as one of the most promising solutions to meet the needs of the fifth-generation (5G) broadband wireless communication systems in terms of higher spectral and energy efficiency [1]. In most previous papers in the literature, the maximization of energy efficiency (EE) or the total data rate of tiers in HetNets was formulated as a single objective optimization problem (SOOP) [2]–[5]. In [2], the authors investigated the power and bandwidth allocation in orthogonal frequency division multiple access (OFDMA) HetNets to maximize the energy efficiency of all small cell users while satisfying the constraints on the power and data rate. In [3], network throughput maximization problem in a downlink HetNet was first formulated and then a low-complexity resource allocation algorithm was proposed. The design of energy-efficient resource allocation for HetNets wireless network with multihomed user equipments was investigated in [4]. In [5], the joint load balancing and interference management in HetNets was devised where an iterative algorithm based on successive convex programming was proposed. To the best of our knowledge, the performance tradeoff in terms of EE or data rate between different tiers has never been investigated in the literature. To this end, in this letter, we study this tradeoff by using a multiobjective optimization problem (MOOP).

To analyze the tradeoff between conflicting objectives in wireless systems, MOOP has been employed recently in [6]–[8]. In [6], interference efficiency was introduced as a new performance metric in underlay cognitive radio networks to maximize ergodic sum rate and minimize the average interference power on the primary receiver, simultaneously. The work in [7] simultaneously optimized data rates and harvested powers as a general MOOP while considering multiuser multiple-input multiple-output broadcast networks implementing simultaneous wireless information and power transfer. In [8], a resource allocation scheme for a simultaneously wireless information and power transfer (SWIPT) network with non-linear energy harvesting model was studied as a MOOP where the weighting sum method was proposed. In practice, maximizing EE or throughput between tiers are both desirable. However, it is expected that there is a non-trivial tradeoff between tiers, as users in each cell experience interference from other cells and their achievable rates are affected by the received interference power from other base stations. In contrast to [1]–[5], here an energy efficiency or throughput maximization as a MOOP is considered in OFDMA HetNets to investigate the performance tradeoff between tiers. Furthermore, this performance tradeoff can enhance the load balancing between different tiers. Hence, by using adjustable weighting parameters, a service provider has a degree of freedom in executing resource allocation policy to balance the load between different tiers. Moreover, considering this tradeoff provides fairness among the tiers. In fact, this letter avoids to connect the considerable majority of users to the macrocell while the small cells become still without any user. This motivates us to formulate our problem as a MOOP in which the performance of macrocell and the small cells are jointly maximized. In this problem, the optimal subchannel assignment and power allocation should be found for each cell. To solve the formulated non-convex MOOP, we first employ the weighted Tchebycheff method which transforms the MOOP into a SOOP by introducing a new parameter [10]. Different weights are given to different cells in this method representing the beneficial coefficient of the heterogeneous cells in providing rate and allocated power for users. Note that the weighted Tchebycheff method is able to generate every Pareto optimal solution even if the problems are non-convex functions with a low computational complexity. Then, in order to solve the obtained SOOP, we propose

Manuscript received April 16, 2019; accepted May 22, 2019. Date of publication May 28, 2019; date of current version October 11, 2019. This work was supported in part by EOS through the Belgian Research Councils FWO and FNRS under Grant 30452698. The work of D. W. K. Ng was supported by the Australian Research Council's Discovery Project under Grant DP190101363. The associate editor coordinating the review of this paper and approving it for publication was X. Chu. *(Corresponding author: Mohammad Robat Mili.)*

M. R. Mili and H. Steendam are with the Department of Telecommunications and Information Processing, Ghent University/IMEC, 9000 Ghent, Belgium (e-mail: mohammad.robatmili@ieee.org; heidi.steendam@ugent.be).

A. Khalili is with the Department of Computer Engineering and IT, Amirkabir University of Technology, Tehran 1766645157, Iran (e-mail: ata.khalili@ieee.org).

D. W. K. Ng is with the School of Electrical Engineering and Telecommunications, University of New South Wales, Sydney, NSW 2052, Australia (e-mail: w.k.ng@unsw.edu.au).

Digital Object Identifier 10.1109/LWC.2019.2919565

an iterative resource allocation algorithm that decouples the subchannel assignment and power allocation to obtain a locally optimal solution.

II. System Model

In our scenario, we assume a general multi-tier HetNet model, where a high power macrocell is considered as the basic tier while the other tiers consist of small cells with low-power base stations, such as picocells and femtocells. Define the set of all base stations as $\{0, 1, 2, \ldots, N\}$, where index 0 refers to the macrocell and $\mathcal{N} = \{1, 2, \ldots, N\}$ denotes the set of low-power base stations, which are deployed within the coverage area of the macrocell base station to increase data rate. As the macrocell and the other cells work under co-channel deployment, they incur some inter-cell interference. In this letter, we focus on downlink transmissions with a bandwidth B that is divided into $\mathcal{M} = \{1, \ldots, M\}$ subchannels. Each subchannel has $B_c = B/M$ Hz bandwidth. We assume that in tier n, $(0 \le n \le N)$, $\mathcal{U}_n$ is the set of U_n users served by the nth base station. The power allocated to the mth subchannels in cell n is denoted by p_n^m. We denote the instantaneous channel power gains for the link between the nth base station and the lth user on the mth subchannel as $h_{n,l}^m$. User l on the subchannel m receives its signals and the interference signals from other cells. The noise power is N_0. The instantaneous received signal-to-interference-plus-noise ratio (SINR) at receiver l in cell n on subchannel m is

$$\mathrm{SINR}_{n,l}^m = \frac{p_n^m h_{n,l}^m}{N_0 + \sum_{\substack{j=0 \\ j \neq n}}^{N} p_j^m g_{j,l}^m}, \tag{1}$$

where $g_{j,l}^m$ is the interference channel gain coming from other cells on user lth in cell n on subchannel m.

In particular, the performance tradeoff between different tiers in HetNets is an interesting but challenging optimization problem, since they are usually coupled and conflicting. This is because such networks under co-channel deployment suffers from inter-cell interference that is originated from users in different tiers. This motivated us to formulate our problem as a MOOP to study the tradeoff between all cells in our scenario.

III. MOOP Formulation

In this section, in order to investigate a performance tradeoff between different cells of HetNets, we jointly maximize the EE (and alternatively the sum rate) of the macrocell and the small cells. This optimization is constrained for maximum total transmit power in each base station as well as minimum rate for each tiers. Such joint constrained optimization can be formulated through the following MOOP:

$$\max_{\mathbf{p},\boldsymbol{\rho}} \; EE_n = \frac{\sum_{m=1}^{M} \sum_{l=1}^{U_n} \rho_{n,l}^m \ln\left(1 + \mathrm{SINR}_{n,l}^m\right)}{\sum_{m=1}^{M} p_n^m + P_n^{cir}}, \; \forall n, \tag{2a}$$

$$\text{s.t.} \quad \sum_{m=1}^{M} p_n^m \le P_{n,\max}, \quad \forall n, \tag{2b}$$

$$\sum_{m=1}^{M} \sum_{l=1}^{U_n} \rho_{n,l}^m \ln\left(1 + \mathrm{SINR}_{n,l}^m\right) \ge R_{n,\min}, \forall n, \tag{2c}$$

$$\sum_{l=1}^{U_n} \rho_{n,l}^m \le 1, \quad \forall m, n, \tag{2d}$$

$$\rho_{n,l}^m \in \{0, 1\}, \quad \forall n, m, l, \tag{2e}$$

where $\rho_{n,l}^m$ is a binary variable indicating the subchannel assignment such that $\rho_{n,l}^m = 1$ if subchannel m is assigned to users l in cell n and $\rho_{n,l}^m = 0$, otherwise. Also, $\mathbf{p} \in \mathbb{R}^{MU_N \times 1}$ and $\boldsymbol{\rho} \in \mathbb{Z}^{MU_N \times 1}$ are the collections of power allocation and subchannel assignment variables for all cells. P_n^{cir} is a constant value denoting the circuit power consumption of the base station in cell n. $P_{n,\max}$ is the maximum total transmit power of the base station in cell n. $R_{n,\min}$ is the minimum required rate for each tiers. The objective function EE in (2a) can be replaced by a MOOP where the sum rate of each cell (the numerator of EE) is maximized while the total transmission power of each base station (the denominator of EE) is minimized, simultaneously [11]. The underlying problem can be solved through the weighted Tchebycheff method, which is formally stated as

$$\min_{\mathbf{p},\boldsymbol{\rho},\chi} \quad \chi \tag{3a}$$

$$\text{s.t.} \quad \frac{\alpha_n}{|C_n|}\left(C_n - \sum_{m=1}^{M} \sum_{l=1}^{U_n} \rho_{n,l}^m \ln\left(1 + \mathrm{SINR}_{n,l}^m\right)\right) \tag{3b}$$

$$-\chi \le 0, \quad \forall n,$$

$$\frac{\beta_n}{|P_n|}\left(\sum_{m=1}^{M} p_n^m - P_n\right) - \chi \le 0 \; \forall n, \tag{3c}$$

$$\text{s.t.} \qquad (2b) - (2e),$$

where χ is an additional auxiliary optimization variable. It should be noted that $|C_n|$ and $|P_n|$ indicate the normalization factors. Moreover, $\alpha_0, \alpha_1, \ldots, \alpha_N$ and $\beta_0, \beta_1, \ldots, \beta_N$ denote the weighting coefficients indicating the importance of different objectives such that $\alpha_0 + \alpha_1 + \cdots + \alpha_N + \beta_0 + \beta_1 + \cdots + \beta_N = 1$. Note that by assuming $\beta_0 = \beta_1 = \cdots = \beta_N = 0$, we are able to find a sum rate tradeoff between different tiers. The weighted Tchebycheff method can provide a complete Pareto-optimal set by changing the coefficient weights assuming that $C_0, C_1, \ldots, C_N$ and $P_0, P_1, \ldots, P_N$ are the optimal objective values with respect to each objective [10]. In fact, they can be considered as the maximum rate and minimum transmit power at different cells. It is worth mentioning that a solution that is as close as possible to the Utopia point is Pareto optimal [10]. Here, χ can be viewed as a parameter to evaluate the performance between the different tiers in HetNets.

Problem (3) is a non-convex mixed integer non-linear problem (MINLP) due to the binary constraint in (2e) and the existence of the interference terms in the SINR in (1). As can be seen in constraint (3b), the different optimization variables, i.e., power allocation and subchannel assignment are coupled with each other. This type of problems is among the most challenging problems in which obtaining the globally optimal solution for large networks is practically impossible. The complexity of the approaches to deal with these problems grows exponentially. Therefore, we decouple this problem into two subproblems to reduce the required computational complexity, and design an iterative solution where the subchannel assignment and power allocation are performed iteratively to obtain a locally optimal solution. In the following, we first discuss the subchannel allocation.

Here, we first attempt to find the optimal subchannel assignment for users when a feasible power allocation for all subchannels in all cells is given. At iteration t, the subchannel allocation $\rho_{n,l}^m[t]$ is determined based on the power allocation $p_{n,l}^m[t-1]$ in the previous iteration as:

$$\rho_{n,l}^m[t] = \begin{cases} 1, & \text{if } l = \arg\max_l \ \ln\Big(1 + \mathrm{SINR}_{n,l}^m[t-1]\Big), \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

To initialize the iterative algorithm, we start by computing a feasible solution $(\rho[0], \mathbf{p}[0])$.[1] Suppose that the subchannel assignments for a given power $\mathbf{p}[t-1]$ are settled at this iteration. Then with the chosen $\rho[t]$, the optimization problem is formulated to obtain the power allocation. In this regard, we can omit $\rho_{n,l}^m$ wherever it appears. However, the optimization problem is still non-convex due to the incorporating interference in the rate function. To deal with this issue, we use successive convex approximation. In this method, instead of dealing with the highly non-concave rate function, we establish a concave lower bound for the rates, by using the following inequality [12]:

$$v_n^m \ln z_n^m + w_n^m \le \ln(1 + z_n^m), \tag{5}$$

which is tight (exact) at $z_n^m = \hat{z}_n^m \ge 0$ when the approximation constants are chosen as

$$v_n^m = \frac{\hat{z}_n^m}{1 + \hat{z}_n^m}, \tag{6}$$

$$w_n^m = \ln(1 + \hat{z}_n^m) - \frac{\hat{z}_n^m}{1 + \hat{z}_n^m} \ln(\hat{z}_n^m). \tag{7}$$

The relations (5)-(7) can be obtained from equating the slope and function values at $\hat{z}_n^m$ giving a unique correspondence between each $\hat{z}_n^m$ and the pair $\{v_n^m, w_n^m\}$. These equations were first derived in [12] to formulate the successive convex approximation for low-complexity (SCALE) algorithm for multiuser power control over cross-talk-corrupted digital subscriber line (DSL) systems. Using the approximation (5) and defining $\tilde{p}_n^m = \ln(p_n^m)$ ([9] for $\forall m, n$), the optimization problem (3) is transformed into the following optimization

$$\min_{\tilde{\mathbf{p}},\chi} \quad \chi(\tilde{\mathbf{p}}) \tag{8a}$$

$$\text{s.t} \quad \frac{\alpha_n}{|C_n|}\left(C_n - \left(\sum_{m=1}^{M}\sum_{l=1}^{U_n} v_n^m \ln\left[\frac{e^{\tilde{p}_n^m} h_{n,l}^m}{N_0 + \sum_{\substack{j=0\\ j\neq n}}^{N} e^{\tilde{p}_j^m} g_{j,n}^m}\right] + w_n^m\right)\right) - \chi \le 0, \quad \forall n, \tag{8b}$$

$$\frac{\beta_n}{|P_n|}\left(\sum_{m=1}^{M} e^{\tilde{p}_n^m} - P_n\right) - \chi \le 0 \qquad \forall n, \tag{8c}$$

$$\sum_{m=1}^{M} e^{\tilde{p}_n^m} \le P_{n,\max} \qquad \forall n, \tag{8d}$$

$$\sum_{m=1}^{M}\sum_{l=1}^{U_n}\left(v_n^m \ln\left[\frac{e^{\tilde{p}_n^m} h_{n,l}^m}{N_0 + \sum_{\substack{j=0\\ j\neq n}}^{N} e^{\tilde{p}_j^m} g_{j,n}^m}\right] + w_n^m\right) \ge R_{n,\min}, \forall n. \tag{8e}$$

Note that the log-sum-exp function is convex [9], so optimization problem (8a)-(8e) is a convex problem. The steps for the power control algorithm are shown in Alg. 1 where the original problem (3) is solved by tightening the bound in (8a)-(8e) while updating v_n^m and w_n^m. In the first iteration, we initialize $v_n^m = 1$ and $w_n^m = 0$ and in the next iterations, v_n^m and w_n^m are updated based on (6) and (7) where $\hat{z}_n^m = \frac{e^{\tilde{p}_n^m} h_{n,l}^m}{N_0 + \sum_{\substack{j=0\\ j\neq n}}^{N} e^{\tilde{p}_j^m} g_{j,n}^m}$.

Lemma 1: In Alg. 1, the obtained result at each iteration monotonically improves so that the sequence converges to the point that the logarithmic approximation (8a)-(8e) is exact.

Proof: To prove this lemma, we first define two functions as

$$C_n'(p_n^m) = \left(C_n - \sum_{m=1}^{M} \ln\left(1 + \frac{p_n^m h_{n,l}^m}{N_0 + \sum_{\substack{j=0\\ j\neq n}}^{N} p_j^m g_{j,l}^m}\right)\right) \tag{9}$$

$$\tilde{C}_n(\tilde{p}_n^m, v_n^m, w_n^m) = \left(C_n - \left(\sum_{m=1}^{M} v_n^m \times \ln\left[\frac{e^{\tilde{p}_n^m} h_{n,l}^m}{N_0 + \sum_{\substack{j=0\\ j\neq n}}^{N} e^{\tilde{p}_j^m} g_{j,n}^m}\right] + w_n^m\right)\right). \tag{10}$$

At the *i*th iteration, we assume that the previous iteration $\{p_n^m(i-1)\}$ is a feasible solution to the optimization problem (8a)-(8e). It is obvious that for $i = 1$, the all-zero vector is feasible for optimization problem (8a)-(8e), however, for $i > 1$, it should be

$$\begin{aligned} &\tilde{C}_n(\tilde{p}_n^m(i), v_n^m(i), w_n^m(i)) \ge C_n'(p_n^m(i)) \\ &= \tilde{C}_n(\tilde{p}_n^m(i), v_n^m(i+1), w_n^m(i+1)) \end{aligned} \tag{11}$$

In the above equations, the inequality is because of the definition of the bound (5) and equality follows from the tightening step in Alg. 1. Hence, it can be concluded that the minimization in Alg. 1 will decrease the objective function $(\chi(\tilde{\mathbf{p}}))$ at the *i*th iteration, or remain constant. ■

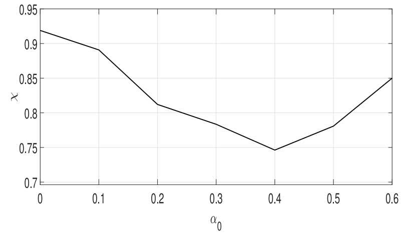
IV. Computational Complexity

Now, we aim at investigating the computational complexity of our proposed algorithm. Taking into account that we need to optimize the sub-channel allocation and the power allocation, we use a two-step approach. In the first step, the best sub-channel for each user is determined via (4) and for the chosen sub-channel the locally optimal power allocation is solved based on the SCALE [12] algorithm using (8). For the optimal sub-channel assignment the order of complexity is $\mathcal{O}(NMU)$, and for the power allocation is $\mathcal{O}(NMU)(4N)$. Moreover, when the CVX is employed, it employs SCALE approach with the interior point method and the number of required iterations for this approach is $\frac{\log(4N)/i^0\delta}{\log(\epsilon)}$, where i^0 is the initial point, $0 < \delta \ll 1$ is the stopping criterion, and ϵ is used for updating the accuracy of the method.

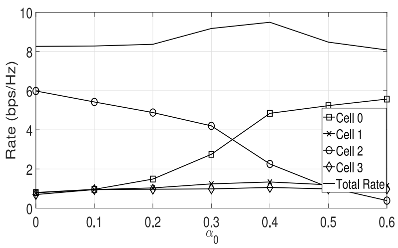
V. Numerical Results

In this section, we present the numerical results for the tradeoff between the performance of different tiers in a HetNet. We assume $M = 4$, the number of cells are 4, $P_{0,\max} = 43$ dBm, $P_{1,\max} = 35$ dBm, $P_{2,\max} = 38$ dBm and $P_{3,\max} = 30$ dBm, $R_{\mathrm{n,min}} = R_{\min} = 0.1$ bps/Hz. Also, the same value of $P_{\mathrm{n}}^{\mathrm{cir}} = 30$ dBm for all base stations is assumed. For the

[1] To find $\rho[0]$, we start with this case where no interference exists between cells.



(a)



(b)

Fig. 1. Throughput tradeoff between tiers. (a) χ vs. weighting coefficient α_0. (b) Rate in each cell vs. weighting coefficient α_0.

Algorithm 1 Iterative Power Allocation Algorithm Using Series of Concave Approximations Method

---

Initialize $i = 0$ and $p_n^m[0]$, $v_n^m[0] = 1$ and $w_n^m[0] = 0$
Repeat
Solve the optimization problem (8a)-(8e) using optimization package incorporated with interior point method to find $\tilde{p}_n^m[i]$
Tighten: update $v_n^m[i]$ and $w_n^m[i]$ at $\hat{z}_n^m$ with (6) and (7)
$i = i + 1$
Until Convergence

---

wireless channel model, each subchannel experiences Rayleigh fading which includes the pathloss component as $128.1 + 37.6$ log (d), in which d is the distance of BS to user in km. Additional auxiliary optimization variable (χ) and the rate of each cell against α_0 are plotted in Fig. 1a and Fig. 1b respectively for $\beta_0 = \beta_1 = \beta_2 = \beta_3 = 0.05$, $\alpha_1 = \alpha_3 = 0.1$, and $\alpha_2 = 0.6 - \alpha_0$. From Fig. 1a, we can observe that by increasing α_0, the additional auxiliary optimization variable decreases until it reaches to the minimum value, $\alpha_0 = 0.4$, and then increases. From Fig. 1b, it is obvious that when α_0 increases, the data rate of cell 0 also increases due to the enhancing the weight of cell 0, whereas the data rate of cell 2 starts to decline with diminishing its weight. On the other hand, due to giving fixed weight to cell 1 and cell 3, the data rate for these two cells are flactuated. It is evident that the minimum value of χ is obtained for $\alpha_0 = 0.4$ which corresponds to the maximum system throughput.

The EE for each cell against β_0 are plotted in Fig. 2 for $\alpha_0 = \alpha_1 = \alpha_2 = \alpha_3 = 0.05$, $\beta_1 = \beta_3 = 0.1$, and $\beta_2 = 0.6 - \beta_0$. In this figure, we change β_0 since the effect of power consumption on EE is generally much more substantial than that of the system throughput. This is due to the fact that EE is directly proportional to the power consumption with a linear scale. In this figure, we observe that while varying β_0 from 0 to 0.6, the weight given to the power consumption of tier 0 increases, leading to a more power decrease and consequently EE increases for tier 0. Meanwhile, by giving less weight to the power consumption of tier 2, the power consumption for tier 2 increases which results into EE decrease for tier 2.

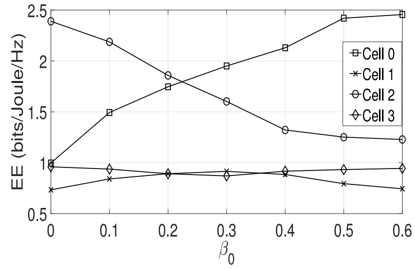


Fig. 2. EE in each cell vs. weighting coefficient β_0.

VI. Conclusion

In this letter, we addressed a tradeoff among the performance of each cell in multi-tier HetNets by formulating a MOOP when the interference between cells is taken into account. The proposed formulation was solved using the weighted Tchebycheff method. Simulation results unveiled that the proposed scheme gives a performance tradeoff among different tiers in the OFDMA-based HetNet that can be changed by considering different weighting coefficient for each tier, denoting their relative importance. Moreover, it can be concluded that the minimum value of χ corresponds to the maximum system throughput where χ behaves as a load balancing factor. In wireless system design, adjusting weighting coefficients depends on several aspects such as the number of users per unit coverage, deployment and maintenance cost, monetary issues, etc.

References

[1] V. W. Wong, R. Schober, D. W. K. Ng, and L. C. Wang, *Key Technologies for 5G Wireless Systems*. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[2] H. Zhang, H. Liu, J. Cheng, and V. C. M. Leung, "Downlink energy efficiency of power allocation and wireless backhaul bandwidth allocation in heterogeneous small cell networks," *IEEE Trans. Commun.*, vol. 66, no. 4, pp. 1705–1716, Apr. 2018.

[3] J. Niu, G. Y. Li, Y. Li, D. Fang, and X. Li, "Joint 3D beamforming and resource allocation for small cell wireless backhaul in HetNets," *IEEE Commun. Lett.*, vol. 21, no. 10, pp. 2286–2289, Oct. 2017.

[4] R. Liu, M. Sheng, and W. Wu, "Energy-efficient resource allocation for heterogeneous wireless network with multi-homed user equipments," *IEEE Access*, vol. 6, pp. 14591–14601, 2018.

[5] H. H. M. Tam, H. D. Tuan, D. T. Ngo, T. Q. Duong, and H. V. Poor, "Joint load balancing and interference management for small-cell heterogeneous networks with limited backhaul capacity," *IEEE Trans. Wireless Commun.*, vol. 16, no. 2, pp. 872–884, Feb. 2017.

[6] M. R. Mili and L. Musavian, "Interference efficiency: A new metric to analyze the performance of cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 16, no. 4, pp. 2123–2138, Apr. 2017.

[7] J. Rubio, A. Pascual-Iserte, D. P. Palomar, and A. Goldsmith, "Joint optimization of power and data transfer in multiuser MIMO systems," *IEEE Trans. Signal Process.*, vol. 65, no. 1, pp. 212–227, Jan. 2017.

[8] H.-V. Tran, G. Kaddoum, and K. T. Truong, "Resource allocation in SWIPT networks under a nonlinear energy harvesting model: Power efficiency, user fairness, and channel nonreciprocity," *IEEE Trans.Veh. Technol.*, vol. 67, no. 9, pp. 8466–8480, Sep. 2018.

[9] H.-V. Tran, G. Kaddoum, H. Tran, and E.-K. Hong, "Downlink power optimization for heterogeneous networks with time reversal-based transmission under backhaul limitation," *IEEE Access*, vol. 5, pp. 755–770, 2017.

[10] K. Miettinen, *Nonlinear Multiobjective Optimization*. Boston, MA, USA: Kluwer, 1999.

[11] C. He, B. Sheng, P. Zhu, X. You, and G. Y. Li, "Energy- and spectral-efficiency tradeoff for distributed antenna systems with proportional fairness," *IEEE J. Sel. Areas Commun.*, vol. 31, no. 5, pp. 894–902, May 2013.

[12] J. Papandriopoulos and J. S. Evans, "SCALE: A low-complexity distributed protocol for spectrum balancing in multiuser DSL networks," *IEEE Trans. Inf. Theory*, vol. 55, no. 8, pp. 3711–3724, Aug. 2009.