

Renewable Energy Distribution in Cooperative Cellular Networks with Energy Harvesting

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Abstract—In this paper, we propose a novel online centralized algorithm for energy cooperation among energy harvesting capable base stations (BSs) in multi-tier cellular networks. BSs are connected to the non-renewable source used by a BS when it cannot harvest sufficient energy to serve its connected users. BSs with the extra harvested energy operate cooperatively and share their surplus energy with BSs that have not harvested sufficient energy. To stimulate BSs with energy deficit to use the shared energy of other BSs, an energy pricing framework is established which results in reducing of the non-renewable energy consumption. We formulate the problem of maximizing the fairness of the renewable energy distribution. The closed-form of energy share given to each BS with energy deficit is found, by which the renewable energy distribution fairness is maximized. Energy is shared by the smart grid. The problem of minimizing the smart grid usage cost for distributing energy is formulated and an online algorithm is proposed to approximate its solution. Simulation results show that the approximate algorithm reduces the non-renewable energy consumption significantly and reduces the cost of smart grid usage near to the optimal solution.

I. INTRODUCTION

Deploying small cells (e.g., femtocells and picocells) along with traditional macrocells in cellular networks is a promising solution to meet the exploding demand of the capacity and coverage [1]. Depending on their capabilities, small cell base stations (BSs) are classified into different types such as microcells, picocells and femtocells. Various technical challenges raise when such cells are deployed such as resource assignment, power allocation and interference management. Since small cells has short coverage and limited power consumption, one can think of running those devices using battery power. To make the cellular network green, energy harvesting from renewable energy sources for better charging has received attention. Harvesting energy from the sources like solar and wind power is a thriving economical approach for reducing the use of fossil energy resources [2], [3]. In such cases, one need to model both the battery charging behavior as well as user power consumptions.

Energy harvesting receivers are considered in [4] where channel state information is used in order to find an adaptive energy beamforming to supply energy to receivers. The power consumption model of BSs from different types in cellular networks is investigated in [5]. In [5], the relation between the BSs transmit power and the users requested traffic rates is obtained. In [6], a heterogeneous network is studied where BSs in different tiers are self-powered. If a BS has not harvested sufficient energy, it is kept OFF for charging energy, and its connected users are served by neighbouring BSs which are ON. In [7], the authors study a non-cooperative game among storage

units. In order to maximize its utility, each storage unit decides strategically on the amount energy to sell in a local market. The energy exchange is done by the smart grid. The game is guaranteed to have at least one Nash equilibrium. Energy cooperation in energy harvesting networks has been explored recently, for instance, in [8], [9], where harvesting modules share a portion of their harvested energy with other harvesting modules. In [8], the optimal energy cooperation among a source and a relay is found that maximizes the network throughput.

The energy cooperation between two cellular BSs equipped with harvesting and hybrid modules is studied in [9]. In [9], the harvested energy and the demanded energy are considered to be deterministic and the optimal energy cooperation policy of BSs is derived. In [10], the joint energy and communication cooperation approaches for energy cost saving in cellular networks is studied where the smart grid facilitates two-way energy exchange. The joint design and combination of the physical layer technique of the coordinated multi-point (CoMP) with two way energy trading is studied in [11], where BSs are connected to the smart grid. In contrary to these solutions which considers trade with smart grid, in our framework, the harvested energy is not traded between the BS and the grid. We propose a framework for energy exchange among BSs by which one can combat the effect of the intermittent nature of the harvested energy from non-renewable source. A non-cooperative Stackelberg game between the residential units of energy and the shared facility controller is proposed in [12] to explore how both entities can benefit from their energy trading with each other and the grid. Optimal energy management decisions to minimize the total electricity cost and the operation delay is investigated in [13] where users are connected to smart grid.

In this paper, an online centralized approach for reducing the non-renewable energy consumption in multi-tier cellular networks with energy harvesting capability is studied. We assume that the harvested and the demanded energy from BSs have stochastic nature. BSs with the extra harvested energy operate cooperatively and share their surplus energy with BSs that have not harvested sufficient energy. To stimulate BSs with energy deficit to utilize the harvested energy of other BSs, an energy pricing framework is established resulting in reducing the non-renewable energy consumption. By using the Jain's fairness index, the fairness of the renewable energy distribution is quantified. We formulate the problem of maximizing the fairness of the renewable energy distribution. We derive an equation which shows the share each BS with deficit energy receives such that the fairness between BSs is maximized. Energy is shared by the smart grid. When BSs share their energy using the smart grid, the grid operator charges a cost for such service. This cost increases as the amount of the shared energy and the distance among BSs increases. The problem of minimizing the smart grid

usage cost for distributing energy is formulated and an online algorithm is proposed to approximate its solution. Simulation results show that the approximate algorithm reduces the non-renewable energy consumption significantly and reduces the cost of smart grid usage near to the optimal solution. The cost of installing large batteries is removed as the proposed algorithm is applied and the waste of energy in limited batteries reduces.

The rest of this paper is organized as follows. The system model is given in Section II. Our proposed energy distribution frameworks is presented in Section III and performance evaluations are given in Section VI.

II. SYSTEM MODEL

Consider the downlink of a small cell network that encompasses K tiers of BSs. Assume that BSs operating in tier k are distributed according to a Poisson Points Process (PPP) with density λ_k . Without lack of generality, we assume that the only source of energy consumption in a BS is the energy used to serve the connected users. The downlink transmit power of a BS operating in tier k is P_k . The distribution of the users follows a PPP with density λ_u and each user is allowed to connect to only one BS. Tiers are unbiased and a user connects to a BS with the highest average received signal power. As the transmit power and densities of BSs operating in different tiers are not identical, the number of users served by BSs are not equal. The average number of users that a BS of tier k serves is [6]

$$N_k = \frac{P_c \lambda_u P_k^{\frac{2}{\gamma}}}{\sum_{j=1}^K \lambda_j P_j^{2/\gamma}}, \quad (1)$$

where γ is the pass loss exponent considered equal for all the tiers. Moreover, P_c is the coverage probability and denotes the portion of the users connected to a BS with SINR above than a threshold. We consider a time-slotted system where a user demands a traffic rate in bits per second at the beginning of each time slot from the connected BS. The demanded rate has a stochastic nature and it is assumed to be constant during a time slot. Let $R_{i,k}^m(t)$ and $p_{i,k}^m(t)$ respectively denote the demanded rate of the user m connected to the i^{th} BS of tier k at time slot t and the power consumption of the BS in Watts to provide the user with its demanded rate. Due to the stochastic nature of demanded rates of connected users, the consumed power at BSs is stochastic. The consumed power to serve each user connected to a BS can be modeled as an arbitrary random process. The number of connected users to the i^{th} BS operating in tier k at time slot t is denoted by $N_k^i(t)$. It is modeled as a Poisson random variable [5], where its mean value is given in (1). If $p_k^i(t)$ denotes the consumed power of the i^{th} BS of tier k at time slot t , we have $p_k^i(t) = \sum_{m=1}^{N_k^i(t)} p_{i,k}^m(t)$. Since the consumed power is constant throughout the time slot, the consumed energy is $T p_k^i(t)$ Joules where T is the time slot duration.

The BSs harvest energy from environment. The amount of the harvested energy of the i^{th} BS of tier k at time slot t is denoted by $\mu_k^i(t)$. It has a stochastic nature. In our model, we have no restriction on the distribution of this variable. A BS stores the harvest energy in its battery and its capacity is limited. We assume that all the BSs of tier k have similar battery capacities of c_k . The harvested energy is wasted if the battery is full. Let $e_k^i(t)$ denote the battery level of the i^{th} BS of tier k at time slot t . As the harvested energy has stochastic nature, it is possible that in some time slots, the harvested energy by a BS is more than the required energy to serve its connected users. On the other hand, in some time lots, the harvested energy is

not sufficient to serve its connected users. The BS is compelled to compensate its energy deficit in such cases.

To compensate their energy deficit, BSs are connected to the non-renewable energy source. To reduce the non-renewable energy consumption, we allow a BS with extra harvested energy to share its surplus energy with BSs with energy deficit. The energy exchange between BSs is carried out using the smart grid. A smart grid enables a precise measurement of the electric power by using digital devices which can communicate with each other. When the BSs share their energy using the smart grid, the smart grid operator charges a cost for such service. This cost is an increasing function of the distance as well as the amount of the shared energy [14]. In our model, we assume that distances between BSs are known. It is supposed that the energy transfer from a BS to other BSs is possible. Assume that the i^{th} BS of tier k shares $E_S(t)$ Joules with other BSs or receives $E_S(t)$ Joule from other BSs. Its battery level is updated as

$$e_k^i(t+1) = \min \{ \max \{ e_k^i(t) - T p_k^i(t), 0 \} + \mu_k^i(t) \pm E_S(t+1), c_k \}, \quad (2)$$

where $E_S(t)$ is added if the BS receives energy, or it is subtracted if the BS shares its extra stored energy with other BSs. In (2), the maximum stored energy in the battery is equal to the battery capacity. Furthermore, the BS can not use more energy than the stored amount from its battery.

III. RENEWABLE ENERGY DISTRIBUTION FRAMEWORKS

Based on the system model presented in the previous section, we build a framework for energy exchange between BSs. The goal is to reduce the non-renewable energy consumption performed such that the maximum of the renewable energy distribution fairness is attained. Simultaneously, the cost of using the smart grid for renewable energy distribution among BSs with energy deficit is minimized. Consider that the energy consumption by a BS to serve a user costs a known price of φ units of money per Joule for the user. Moreover, the used non-renewable energy costs ζ units of money per Joule for a BS where $\varphi < \zeta$. In order to make the financial transactions, a *Credit Clearance Service* (CCS) is used [15], [16], where all the BSs have credit accounts with initial fund. We assume that the CCS is also the network control center.

At the beginning of each time slot, all the BSs send a message to the CCS which contains the information of the amount of energy they are willing to share or receive. Based on these information, the BSs are divided into two groups, i.e., BSs with extra harvested energy and BSs with energy deficit. Let \mathcal{S} denote the set of BSs with extra harvested energy, where $n = |\mathcal{S}|$ denotes its cardinality. We denote the i^{th} BS in \mathcal{S} by s_i . The set of BSs with energy deficit is denoted by \mathcal{B} and its cardinality is $n' = |\mathcal{B}|$. We denote the j^{th} BS in \mathcal{B} by b_j . We update our notation for the battery level, the number of connected users and the demanded power based on our new definitions as follows. $e_{s_i}(t)$, $N_{s_i}(t)$ and $p_{s_i}(t)$ are used for the BS s_i with the extra harvested energy, and $e_{b_j}(t)$, $N_{b_j}(t)$ and $p_{b_j}(t)$ are used for the BS b_j with energy deficit, respectively. The cost of transferring a unit of energy from BS s_i to BS b_j is captured by an increasing function $\Gamma(g_{s_i,b_j})$ where g_{s_i,b_j} is the distance between BSs s_i and b_j in meters. We assume that $\Gamma(g_{s_i,b_j}) < \varphi, \forall s_i \in \mathcal{S}, \forall b_j \in \mathcal{B}$. This inequality is used to show that the non-renewable energy costs more than the shared energy of other BSs, and thus, a BS is motivated to compensate its energy deficit by the extra stored energy of other BSs. Moreover, this inequality ensures that a BS with energy deficit has incentive

to compensate its energy shortage with extra stored energy of other BSs to serve connected users. The cost of the smart grid usage is paid by the BS receiving the energy (i.e., BS with energy deficit). Let $\rho_{s_i}(t)$ denote the amount of extra energy the BS s_i is willing to share at time slot t . Then, we find

$$\rho_{s_i}(t) = e_{s_i}(t) - T p_{s_i}(t). \quad (3)$$

The amount of the required energy of the BS b_j at time slot t is

$$\rho_{b_j}(t) = |e_{b_j}(t) - T p_{b_j}(t)|. \quad (4)$$

The total extra energy stored in BSs of the network at time slot t is $\sum_{i=1}^{|\mathcal{S}|} \rho_{s_i}(t)$. The total needed energy of BSs with energy deficit at time slot t is $\sum_{j=1}^{|\mathcal{B}|} \rho_{b_j}(t)$. The utility function of the BS s_i at time slot t is

$$U_{s_i}(t) = \varphi T p_{s_i}(t). \quad (5)$$

The energy share that the BS b_j receives from other BSs is $\eta_{b_j}(t)$. This can be less than the energy that BS b_j needs to serve its users. Let $E_N(t)$ denote the amount of energy purchased from the non-renewable source in time slot t which is $E_N(t) = \rho_{b_j}(t) - \eta_{b_j}(t)$. The utility function of the BS b_j at time slot t is

$$U_{b_j}(t) = \varphi T p_{b_j}(t) - \zeta E_N(t) - \Gamma(g_{s_i, b_j}) \eta_{b_j}(t). \quad (6)$$

We notice that $\Gamma(g_{s_i, b_j}) \eta_{b_j}(t)$ is the cost of sharing $\eta_{b_j}(t)$ Joule between BSs s_i and b_j by the smart grid.

A. Fair Renewable Energy Distribution Scheme

The BSs with extra energy operate cooperatively and share their surplus energy with BSs which are in shortage of energy. As $\varphi < \zeta$ and $\Gamma(g_{s_i, b_j}) < \varphi$, $\forall s_i \in \mathcal{S}, \forall b_j \in \mathcal{B}$, one can obtain $\Gamma(g_{s_i, b_j}) < \zeta$, $\forall s_i \in \mathcal{S}, \forall b_j \in \mathcal{B}$. Thus, BS b_j has incentive to compensate its energy deficit with extra harvested energy of other BSs rather than using non-renewable energy which is more expensive. Since BSs with energy deficit are willing to compensate all their energy deficit with the extra harvested energy of other BSs and the amount of the extra harvested energy is limited, the extra harvested energy should be distributed among all BSs fairly. As BSs have different harvesting rates, the demanded energy and battery capacities, the equal energy share is not fair. To quantify the fairness in a resource allocation problem, various measures have been proposed [17]–[19]. A well-known approach is the one referred by the Jain's index [19]. The Jain's fairness index for allocation of resources among n agents is

$$\text{fairness} = \frac{(\sum_{i=1}^n x_i)^2}{n \sum_{i=1}^n x_i^2}, \quad (7)$$

where x_i is the allocated share to agent i . The Jain's fairness index is between $\frac{1}{n}$ and one, where one denotes the highest fairness and $\frac{1}{n}$ measures the lowest level of fairness [19]. Assume that a resources are divided between n similar agents and each agent's share is a/n . By substituting $x_i = a/n$ in (7), it is observed that the fairness reaches one. In other words, when the agents are similar, the equal share maximizes the fairness. We propose an approach to maximize the fairness of the renewable energy distribution. Each BS may compensate part of its energy deficit with the expensive non-renewable energy. The ratio of the non-renewable energy consumption by the BS b_j to its required energy is $(\rho_{b_j}(t) - \eta_{b_j}(t))/\rho_{b_j}(t)$. The BS b_j is motivated to minimize the consumed non-renewable energy which is equal to minimize this ratio. This is equal to maximizing $\eta_{b_j}(t)/\rho_{b_j}(t)$,

which is the ratio of the received renewable energy to the total needed energy of the BS b_j as $\eta_{b_j}(t)$ is the only variable.

To obtain a fair energy distribution, we use ratio $\eta_{b_j}(t)/\rho_{b_j}(t)$ as the notion of the resource share of BS b_j . We use $\eta_{b_j}(t)/\rho_{b_j}(t)$ instead of x_i in (7). We try to maximize the Jain's index as

$$\begin{aligned} & \max_{\boldsymbol{\eta}_b(t)} \frac{\left(\sum_{j=1}^{n'} \frac{\eta_{b_j}(t)}{\rho_{b_j}(t)} \right)^2}{n' \sum_{j=1}^{n'} \left(\frac{\eta_{b_j}(t)}{\rho_{b_j}(t)} \right)^2} \\ & \text{s.t. } \eta_{b_j}(t) \leq \rho_{b_j}(t), \forall b_j \in \mathcal{B}, \\ & \sum_{j=1}^{n'} \eta_{b_j}(t) = \min \left\{ \sum_{i=1}^n \rho_{s_i}(t), \sum_{j=1}^{n'} \rho_{b_j}(t) \right\}, \\ & 0 \leq \eta_{b_j}(t), \forall b_j \in \mathcal{B}, \end{aligned} \quad (8)$$

where $\boldsymbol{\eta}_b(t) = [\eta^{b_1}(t), \dots, \eta^{b_{n'}}(t)]$ is the vector of energy shares. The first constraint in (8) shows that a given energy share to the BS b_j is less than or equal to its needed energy. The second constraint states that the aggregate energy that the BSs with energy deficit receive from renewable energy sources is equal to minimum of the total extra energy in the BSs (i.e., $\sum_{i=1}^n \rho_{s_i}(t)$) and the shortage of energy in that BSs (i.e., $\sum_{j=1}^{n'} \rho_{b_j}(t)$).

To solve the above optimization problem in (8), we investigate the convexity of the objective function and the constraints. The constraints are linear, and therefore, they are affine. It is straightforward to show that the objective function is neither convex nor concave in its domain. The maximum of the objective function is one [19]. Since the objective function is neither convex nor concave, by applying KKT conditions, we can find the local and global extremums or saddle points [20]. The global maximum point of the above optimization, is found by the following theorem.

Theorem 1: The global maximum point of the optimization problem formulated in (8) that satisfies all constraints is

$$\eta_{b_j}^*(t) = \frac{\rho_{b_j}(t) \min \{ \sum_{i=1}^n \rho_{s_i}(t), \sum_{j=1}^{n'} \rho_{b_j}(t) \}}{\sum_{j=1}^{n'} \rho_{b_j}(t)}, \forall b_j \in \mathcal{B}. \quad (9)$$

Proof: The proof is given in [21]. ■

It is observed from (9) that the energy deficit of BSs is compensated totally when the total stored energy in BSs of the network is more than the total demanded energy from BSs. Thus, the non-renewable energy usage is zero in this case. Moreover, when the total stored energy in BSs of the network is less than the total demanded energy from BSs, the entire extra stored energy in the network is used. Next, the renewable energy is distributed such that the total cost of the smart grid usage for sharing energy is minimized. To maintain the fairness maximized, the energy share given to BS b_j is $\eta_{b_j}^*(t)$. Consider that the amount of the shared energy among BSs s_i and b_j is σ_{s_i, b_j} . We assume that $\boldsymbol{\Sigma}$ is the matrix of energy transfer between BSs. The i^{th} element of the j^{th} column of $\boldsymbol{\Sigma}$ is σ_{s_i, b_j} . We use the following optimization problem to minimize the smart grid usage cost

$$\max_{\boldsymbol{\Sigma}} \sum_{i=1}^n \sum_{j=1}^{n'} \Gamma(g_{s_i, b_j}) \sigma_{s_i, b_j}$$

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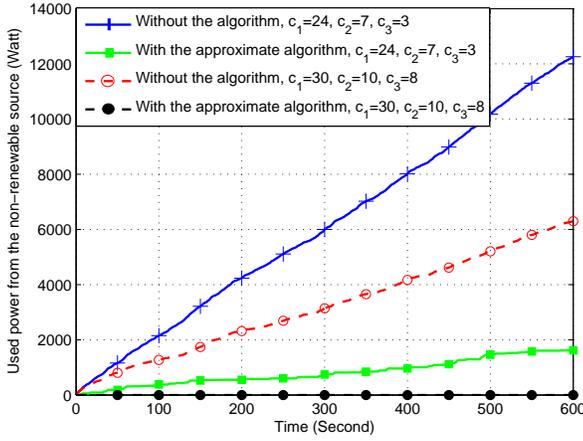


Fig. 1. Comparison of the non-renewable power consumption in the network with and without applying the approximate algorithm.

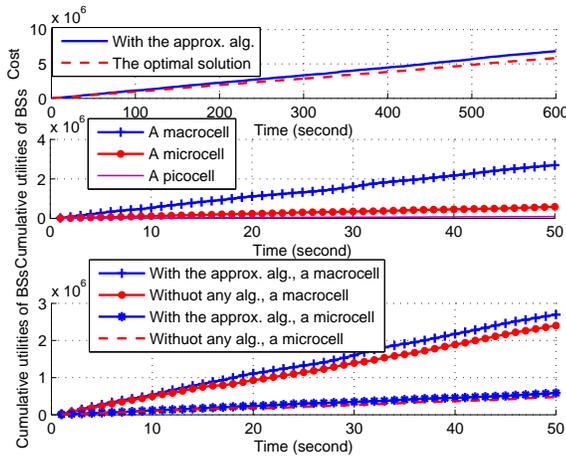


Fig. 2. Plot 1: the cost of the smart grid usage. Plot 2: cumulative utilities of a macrocell and a microcell when the approximate algorithm is applied. Plot 3: comparison of cumulative utilities of a macrocell and a microcell in the presence of the approximate algorithm and without it.

is not applied, the non-renewable energy consumption increases as the harvested energy is wasted in limited batteries.

The smart grid usage cost is depicted in Fig. 2. Reducing the smart grid usage cost increases the utility functions of BSs. Fig. 2 shows that the approximated solution found by the algorithm is near to the optimal solution. Since the algorithm distributes energy according to the closed-form of the energy share formula given in (9), the fairness of the energy distribution is one. The run time of the approximate algorithm for 600 time slots is 1.4 second. The cumulative utility functions of a macrocell, a microcell and a picocell when the approximate algorithm is applied are depicted in Fig. 2. As a BS consumes more energy, it earns more money. Hence, it is seen from Fig. 2 that a macrocell earns more revenue than BSs in the other tiers. The cumulative utilities of a macrocell and a microcell, in the presence of the approximate algorithm and without it, are depicted in Fig. 2. It is observed that when BSs share energy by the smart grid, BSs gain more utilities. Without the algorithm, the utilities of the BSs decrease by the high price of the non-renewable energy. However, with the algorithm, the non-renewable energy consumption reduces, and thus, the utilities of BSs increase. Hence, using the algorithm not only reduces the non-renewable energy consumption, it enhances BSs gained utilities as well.