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# Energy Efficient Hybrid-Powered Communication Systems Using Joint Adaptive Power Allocation and Energy Exchange

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***Abstract*—The spread in the use of wireless services resulted in a remarkable growth of power consumption for telecommunication systems to satisfy the continuous growth of data demand. On the other hand, the emergence of smart grids and the expansion of low-cost distributed powering solutions represented an opportunity to enhance the energy efficiency and improve communication systems' costs. In this paper, we propose to enhance the energy efficiency of self-powered wireless networks by exploiting the possibility of energy exchange between different micro-grids. The objective is to exploit the flexibility and non homogeneity of communication services' demand to maximize the global utility. Cooperation between cells is exploited to exchange additional/needed power as function of their respective users' demands and energy availabilities. While taking into consideration the power losses due to this exchange, we propose an efficient approach to allocate the available resources across the different cells. Numerical simulations show the gains that can be achieved due to this approach as a function of the demand and energy availability variations.**

**Index terms:** Green communications, micro-grids, energy efficiency.

## I. INTRODUCTION

Due to the expansion of usage of communication services, the telecommunications market became one of the highest power consumers. A study by the Center for Energy-Efficient Telecommunications (CEET) and Bell Labs [1] shows that the information communications and technology industry produce more than 830 million tons of carbon dioxide ($CO_2$), which is considered as the main Green House Gas (GHG), annually. This amount represents about $2\%$ of the global $CO_2$ emissions and is equivalent to the proportion produced by the aviation industry as an example. Projections suggest that this share is expected to double by 2020. This study shows also that the wireless devices use only could increase the energy demands of mobile data up to $460\%$ from 9 million MWh (megawatt hours) in 2012 to between $32 - 43$ million MWh by 2015. That growth only represents the same carbon footprint as 4.9 million new cars on the road [1]. This increase has led to a global awareness about the importance of improving energy efficiency and necessity of relying on renewable energy sources for telecommunication networks in order to limit GHG emissions. Although extensive research attempts have been made in the area of energy distribution management as well as in improving energy efficiency of communication systems, combining these two problems together can lead to enhanced energy savings by exploiting the elastic character of the communication components resulting from the flexible demand.

With the technological advances achieved in improving their energy efficiency, renewable sources contributed about $19\%$ of the global world energy consumption in 2012 [2]. In the telecommunications industry, various research studied and developed different resource allocation schemes relying on renewable and heterogeneous power sources [3–6]. One of the challenges when using renewable power sources is their various and uncontrollable supply which makes them unreliable. Thus, a back-up supply is always required. Multiple research works [7–10] have focused on exploiting cooperation in communication systems between the BSs by adjusting the users assignment and optimizing the resource allocation to guarantee the required services while facing power shortages and/or minimizing costs. In [11], a novel scheme is proposed that aims to improve the micro-grids' energy efficiency based on the exchange of surplus power locally. This, not only reduces the global costs, but also the energy losses. In our work, we intend to exploit the capability of power exchange between neighboring base stations to improve the global payoff for the communication system. The challenge, with comparison to the work in [11], is that we exploit not only the energy production variation but also the elasticity of the power consumption in each cell. This can be reached through adaptive power allocation depending on users' requirements and/or channel gains.

We consider a system of inter-connected micro-grids. Each micro-grid covers a cell or sub-group of neighboring cells. Each of them is equipped with different renewable power sources and has the ability to procure power from the main grid when needed. In addition to that, micro-grids can exchange energy when needed. Taking into consideration power losses due to this exchange, the main task is to optimize the amounts of power obtained from each source per micro-grid and the exchanged amounts per link as well as the optimal allocation power per user for each BS for the data communication. To do that, an optimization problem is formulated where

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the objective is to maximize a global system payoff. This payoff combines the reward coming from serving the users as function of the allocated rate from one side and the cost of the procured power from the different sources from the other side. Furthermore, the users' required data-rates as well as the sources and links capacity should be guaranteed. We analyze the problem and propose a sub-optimal solution based on maximizing the utility function on a subspace of the feasibility set. An iterative algorithm is then proposed to determine the generated power per source and the allocation for each user and compute the achievable payoff. Since eventually additional infrastructure needs to be installed (e.g., links and transformers between micro-grids), the proposed scheme can be applied to evaluate the estimated gains with practical distributions and thus justify or not the investment. The contributions of this paper can be summarized as follows:

- We propose a scheme for cooperative joint resource procurement and allocation based on energy exchange to overcome variation of demand and energy supply.
- We formulate a global optimization problem that maximizes the sum of the per micro-grid payoff which addresses the trade-off between service income and energy cost.
- The proposed model accounts for practical power losses through lines and transformers in addition to variable users' demand and energy availability.
- We design a low-cost sub-optimal algorithm based on solving the problem in a subspace of the feasible region.
- Through numerical simulations, we evaluate the gains that can be achieved using the proposed scheme as function of the users' demands and power supplies' variations.

## II. System Model

### A. Network and Powering Architecture

We consider a communication network, as in Fig. 1, composed of a set of BSs aiming to ensure a reliable service for their respective users. The BSs are grouped into $M$ micro-grids according to their location. Each micro-grid is equipped with its internal power sources and connected to the main-grid. In addition to that, the micro-grids are inter-connected so they can exchange energy when needed. $\mathbb{L}_m$, $\mathbb{K}_m$, $\mathbb{S}_m$ denote respectively the set of BSs, the set of users requesting service, and the set of powering sources in the micro-grid $m$.

Any power transfer results in a power loss due to transformers and lines resistance expressed by the function $\epsilon_{i,s}\left(\mathcal{P}\right)$ when transferring a power $\mathcal{P}$ from a source $s$ to a destination $i$ which can be written as shown in [11] as follows

$$\epsilon_{i,s}\left(\mathcal{P}\right) = \begin{cases} \xi_i \mathcal{P} + \frac{(\mathcal{P})^2 R_{i,s}}{U_{i,s}^2}, & \text{if } \mathcal{P} \geq 0 \\ 0, & \text{otherwise,} \end{cases} \tag{1}$$

where $\xi_i$ is the fraction of power lost in the transformer, $R_{i,s}$ is the resistance of the distribution line which depends on the line length, sectional area, and cable material, and $U_{i,s}$ is the distribution voltage. $R_{i,s}$ can be written as

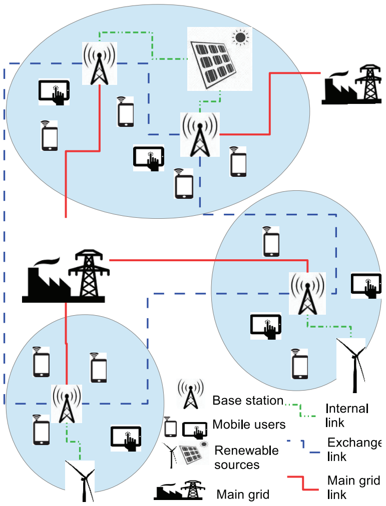

Fig. 1. Network and Powering Architecture.

$$R_{i,s} = \rho_{i,s} \frac{L_{i,s}}{A_{i,s}}, \tag{2}$$

where $\rho_{i,s}$ is the electrical resistivity of the line material (in $\Omega.m^{-1}$), $L_{i,s}$ is the line length, and $A_{i,s}$ is the sectional area of the line.

### B. Micro-Grid Utility Function

The aim of this work is to enhance the energy efficiency by exploiting the possibility of exchanging energy between micro-grids. The objective is to determine the optimal way to efficiently exploit the different power resources by taking profit of exchange links in order to distribute the available energy among them according to their required data rate demands and/or utility. We formulate the problem as a constrained optimization problem where the utility function is devised to address the trade-off between the profit representing the reward of serving the users' requests and the cost of acquiring the needed power from different power sources and exchanging it between the micro-grids. In a general format, the utility function for a micro-grid $m$ is written as follows:

$$\mathcal{U}_m = \sum_{k \in \mathbb{K}_m} \mathcal{R}_{m,k}\left(P_{m,k}^{(u)}\right) - \sum_{s \in \mathbb{S}_m} \mathcal{C}_s^{(g)}\left(P_{m,s}^{(g)}\right), \tag{3}$$

where:

- $\mathcal{R}_{m,k}(P_{m,k}^{(u)})$ is the reward gained from serving the user $k$ with the assigned power $P_{m,k}^{(u)}$. Assuming that users are served over orthogonal channels, the received data rate as a function of the allocated power is written as

$$r_{m,k}\left(P_{m,k}^{(u)}\right) = w_{m,k} \log_2\left(1 + P_{m,k}^{(u)} \gamma_{m,k}\right), \tag{4}$$

where $w_{m,k}$ is the assigned bandwidth, $\gamma_{m,k}$ is the channel gain between the closest BS and the $k$-th user,

and $P^{(u)}_{m,k}$ is the power allocated for transmission for the $k$-th user in the micro-grid $m$.
Considering that each user needs to be served with a minimum required data rate and that it has a maximum decoding rate, the reward function for the data rates is written as

$$\mathcal{R}_{m,k}\left(P^{(u)}_{m,k}\right) = \kappa_{m,k} r_{m,k}\left(P^{(u)}_{m,k}\right) \quad \text{for } r^{min}_{m,k} \le r_{m,k}\left(P^{(u)}_{m,k}\right) \le r^{max}_{m,k}, \tag{5}$$

where $\kappa_{m,k}$ is the data rate unit reward for user $k$, $r^{min}_{m,k}$ and $r^{max}_{m,k}$ are the minimum and maximum data rates, respectively.

- $\mathcal{C}^{(g)}_s(P^{(g)}_{m,s})$ is the cost of acquiring the power $P^{(g)}_{m,s}$ from the source $s$ in the micro-grid $m$. Assuming that the different power sources have limited power generation capacity and that the power cost is linear as function of the procured power with a constant unit power price for each power source, the power cost function is defined as

$$\mathcal{C}^{(g)}_s\left(P^{(g)}_{m,s}\right) = \alpha^{(g)}_{m,s} P^{(g)}_{m,s}, \quad \text{for } 0 \le P^{(g)}_{m,s} \le P^{(g_{max})}_s, \tag{6}$$

where $\alpha^{(g)}_s$ is the unit power price for the power procured from the source $s$ and $P^{(g_{max})}_s$ corresponds to the maximum loading capacity from this source.

### C. Power Exchange Architecture

Considering the possibility of power exchange between micro-grids, ensuring a reliable service for users in each micro-grid is guaranteed if and only if the following condition is satisfied

$$P^{(0)}_m + \sum_{k\in\mathbb{K}_m} \beta_{m,k} P^{(u)}_{m,k} \le \sum_{s\in\mathbb{S}_m} \Psi_{\epsilon_{m,s}}\left(P^{(g)}_{m,s}\right) + \sum_{n\neq m} \Psi_{\epsilon_{m,n}}\left(P^{(t)}_{m,n}\right), \tag{7}$$

where $\Psi_\epsilon(\mathcal{P}) = \mathcal{P} - \epsilon(\mathcal{P})$ is the received power when transferring a power $\mathcal{P}$ through a link with a loss function $\epsilon(\mathcal{P})$. $P^{(g)}_{m,s}$ is the amount of power generated from the source $s$, $P^{(t)}_{m,n}$ the amount of power transferred to/from the micro-grid $n$, and $P^{(u)}_{m,k}$ the power allocated for transmission to a user $k$.

A linear model for the BSs power consumption is considered, where $P^{(0)}_m$ represents the constant power consumption that ensures the operation of the BSs such as cooling and non RF operations while $\beta_{m,k}$ is an amplification factor for the data transmission-dependent consumed power for the BS serving the $k$-th user. Similar models have been widely used in the literature for different types of cells as shown in [12].

## III. POWER PROCUREMENT AND ALLOCATION PROBLEM

### A. Problem Formulation

Maximizing the sum of the the different micro-grids' utilities, we formulate a global optimization problem that considers the possibility of exchanging power across micro-grids while ensuring the required service rate for the different users. The problem is then written as follows

$$\max_{\mathbf{P^{(u)}},\mathbf{P^{(g)}},\mathbf{P^{(t)}}} \sum_{m=1}^{M}\left[\sum_{k\in\mathbb{K}_m} \mathcal{R}_{m,k}\left(P^{(u)}_{m,k}\right) - \sum_{s\in\mathbb{S}_m} \mathcal{C}^{(g)}_s\left(P^{(g)}_{m,s}\right)\right] \tag{8a}$$

$$\text{subject to (7)}, \quad \forall m \in \{1, \vdots, M\}; \tag{8b}$$

$$0 \le P^{(g)}_{m,s} \le P_s^{(g)^{max}}, \quad \forall s \in \mathbb{S}_m,\ \forall m; \tag{8c}$$

$$r^{(min)}_{m,k} \le r_{m,k}\left(P^{(u)}_{m,k}\right) \le r^{(max)}_{m,k}, \quad \forall k \in \mathbb{K}_m,\ \forall m; \tag{8d}$$

$$|P^{(t)}_{m,n}| \le P^{(t)}_{m,n}{}^{max}, \quad \forall n \neq m; \tag{8e}$$

$$P^{(t)}_{m,n} = -P^{(t)}_{n,m}, \quad \forall n \neq m. \tag{8f}$$

The different constraints ensure respectively: (i) reliable powering for each micro-grid, (ii) non violation of power sources' capacity, (iii) respect of the data rate demands per user, (iv) non violation of intra-microgrids transfer lines capacity, where $P^{(t)}_{m,n}{}^{max}$ is the maximum power load on the link between the two micro-grids $m$ and $n$, and (iv) equilibrium of inter-microgrids power transfer.

To solve the problem (8a), we rewrite it focusing on the effective used power per micro-grid from any source in the whole system (not only its own sources). For that, we denote by $P^{(g)}_{m,s_n}$ the portion of the generated power from the source $s_n$ (part of the micro-grid $n$) to be used in the micro-grid $m$.

$$\max_{\mathbf{P^{(g)}},\mathbf{P^{(u)}}} \sum_{m=1}^{M}\left[\sum_{k\in\mathbb{K}_m} \mathcal{R}_{m,k}\left(P^{(u)}_{m,k}\right) - \sum_{n=1}^{M}\sum_{s_n\in\mathbb{S}_n} \mathcal{C}^{(g)}_{s_n}\left(P^{(g)}_{m,s_n}\right)\right] \tag{9a}$$

$$\text{subject to } P^{(0)}_m + \sum_{k\in\mathbb{K}_m} \beta_{m,k} P^{(u)}_{m,k} \le \sum_{n=1}^{M}\sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P^{(g)}_{m,s_n}\right) - \sum_{n\neq m} \epsilon_{m,n}\left(\sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P^{(g)}_{m,s_n}\right)\right), \quad \forall m; \tag{9b}$$

$$\sum_{m=1}^{M} P^{(g)}_{m,s_n} \le P^{(g)^{max}}_{s_n}, \quad \forall s_n \in \mathbb{S}_n,\ \forall n; \tag{9c}$$

$$\sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P^{(g)}_{m,s_n}\right) \le P^{(t)}_{m,n}{}^{max}, \quad \forall n \neq m; \tag{9d}$$

$$r^{(min)}_{m,k} \le r_{m,k}\left(P^{(u)}_{m,k}\right) \le r^{(max)}_{m,k}, \quad \forall k \in \mathbb{K}_m,\ \forall m; \tag{9e}$$

$$P^{(g)}_{m,s_n} \ge 0, \quad \forall s_n \in \mathbb{S}_n,\ \forall n,\ m \in \{1, \vdots, M\}. \tag{9f}$$

The power cost function is convex and the reward rates are non-decreasing concave functions. The power loss functions $\epsilon(.)$ are also convex. The problem (9) is then convex. A sub-gradient method could be adopted to implement an algorithm that iteratively searches the Lagrangian parameters while at each step the power procurement and allocation are determined. Although feasible, this approach results in a very high computation cost which is not scalable for large networks. Thus, we alternatively seek a close-optimal approach with lower computational requirements.

### B. Proposed Resource Allocation Algorithm

In this section, we seek a close-to-optimal approach to solve the problem (9) by considering a tighter feasibility set. The optimal solution of the problem (8a) is lower bounded by the solution of the problem (10) defined as follows

$$\max_{\mathbf{P^{(g)}},\mathbf{P^{(u)}}} \sum_{m=1}^{M} \left[ \sum_{k\in\mathbb{K}_m} \mathcal{R}_{m,k}\left(P_{m,k}^{(u)}\right) - \sum_{n=1}^{M} \sum_{s_n\in\mathbb{S}_n} \mathcal{C}_{s_n}^{(g)}\left(P_{m,s_n}^{(g)}\right)\right] \tag{10a}$$

$$\text{subject to } P_m^{(0)} + \sum_{k\in\mathbb{K}_m} \beta_{m,k} P_{m,k}^{(u)} \leq \sum_{n\neq m} \sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right) - \sum_{n\neq m} \sum_{s_n\in\mathbb{S}_n} \epsilon'_{m,n}\left(\Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right), \quad \forall m; \tag{10b}$$

$$\sum_{m=1}^{M} P_{m,s_n}^{(g)} \leq P_{s_n}^{(g)^{max}}, \quad \forall s_n \in \mathbb{S}_n,\ \forall n; \tag{10c}$$

$$r_{m,k}^{(min)} \leq r_{m,k}\left(P_{m,k}^{(u)}\right) \leq r_{m,k}^{(max)}, \quad \forall k \in \mathbb{K}_m,\ \forall m; \tag{10d}$$

$$\sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}^{(g)}\left(P_{m,s_n}^{(g)}\right) \leq P_{m,n}^{(t)^{\ max}}, \quad \forall n \neq m; \tag{10e}$$

$$P_{m,s_n}^{(g)} \geq 0, \quad \forall s_n \in \mathbb{S}_n,\ \forall n,\ m \in \{1, \vdots, M\}, \tag{10f}$$

where the function $\epsilon'_{m,n}(.)$ is defined as

$$\epsilon'_{m,n}\left(\mathcal{P}\right) = \begin{cases} |\mathbb{S}_n| \frac{R_{m,n}}{U_{m,n}^2}\mathcal{P}^2 + \xi_m \mathcal{P}, & \text{if } \mathcal{P} \geq 0 \\ 0, & \text{otherwise,} \end{cases} \tag{11}$$

where $|\mathbb{S}_n|$ is the number of elements in $\mathbb{S}_n$.

*Proof.* Applying the Cauchy-Schwartz Inequality, we know

$$\left( \sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right)^2 \leq |\mathbb{S}_n| \sum_{s_n\in\mathbb{S}_n} \left(\Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right)^2 \tag{12}$$

From that we deduce

$$\begin{aligned} &\epsilon_{m,n}\left( \sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right) \qquad (13) \\ &= \frac{R_{m,n}}{U_{m,n}^2}\left( \sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right)^2 + \xi_m \sum_{s_n\in\mathbb{S}_n} \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right) \\ &\leq \sum_{s_n\in\mathbb{S}_n} \left[ |\mathbb{S}_n| \frac{R_{m,n}}{U_{m,n}^2} \left(\Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right)^2 + \xi_m \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right] \\ &= \sum_{s_n\in\mathbb{S}_n} \epsilon'_{m,n}\left(\Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right) \end{aligned}$$

which results that the domain limited by the constraint (10b) is included in the domain limited by the constraint (9b). □

Written in this format, the problem (10) is a modified version of classic power allocation problems for multiple cell networks using multiple power sources with the main challenges consisting in 1) the different cells have shared access to multiple power sources, 2) the heterogeneity of the power sources availabilities, and 3) the heterogeneous power losses from the different sources. For each user $k$, we define the effective *usable* power as a function of the amount of power generated from any power source $s_n$ in the network as

$$P_{m,k}^{(r)}\left(P_{m,s_n}^{(g)}\right) = \frac{\Psi'_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)}{\beta_{m,k}}, \tag{14}$$

where

$$\Psi'_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right) = \begin{cases} \Psi_{\epsilon_{m,s_m}}\left(P_{m,s_m}^{(g)}\right), & \text{if } n = m \\ \Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right) - \epsilon'_{m,n}\left(\Psi_{\epsilon_{n,s_n}}\left(P_{m,s_n}^{(g)}\right)\right), & \\ \qquad \text{otherwise.} & \end{cases} \tag{15}$$

From that, we deduce the partial utility of procuring an amount of power $P_{m,s_n}^{(g)}$ from a source $s_n$ by the micro-grid $m$ to be allocated for its $k$-th user as follows

$$\mathcal{U}_{m,k}^{(r)}\left(P_{m,s_n}^{(g)}\right) = \mathcal{R}_{m,k}\left(P_{m,k}^{(r)}\left(P_{m,s_n}^{(g)}\right) + P_{m,k}^{(u)}\right) - \mathcal{C}_s^{(g)}\left(P_{m,s_n}^{(g)}\right), \tag{16}$$

where $P_{m,k}^{(u)}$ is the previously allocated power for user $k$. Based on that, we propose a priority-based allocation scheme in Algorithm 1 where power is procured and allocated iteratively from any source in the network to the user that results in the highest global utility reach independently from the micro-grids to which belongs the user and the source. To guarantee the data rates constraints, users who did not yet satisfied their minimum requirements are given first priority over the other users. For that, we introduce the set $\mathbb{K}^-$ which contains these users. Power allocated per user and availabilities per source are updated after each iteration. This step is repeated iteratively until all users are allocated with their minimum rate requirements and the procurement of additional power decreases the global utility (i.e., its cost is higher than the incurred rate reward) or all power sources are fully harvested. Unlike the optimal solution which requires high computational capability, the proposed algorithm has a linear complexity with limited number of iterations. We will show in the next section the efficiency of the algorithm in terms of close-performance to the optimal solution.

## IV. SIMULATION RESULTS

In this section, we investigate the impact of the proposed scheme on the global system payoff. For that, we compare the obtained payoff using our scheme to the case where no exchange of power between the micro-grids was possible and plot the results as relative gain between the two schemes. Unless otherwise stated, we consider the following system settings. We consider $M = 4$ micro-grids with circular area of diameter 1 $Km$. Each micro-grid contains one BS placed in the center while the users are placed randomly within the cell area. The number of users at each time slot is considered to follow a Poisson point process with average $\mu = 200$ users. The users' channel gains are derived based on their pathloss to their respective BS such that $\gamma_l^{(k)} = c_0\left(\frac{d_0}{d_{l,k}}\right)^{\eta}$, where $c_0$ is the pathloss for the reference distance $d_0$ taken as 10 $dB$ per $Km$, $d_{l,k}$ is the distance between the base-station $l$ and the user $k$, and $\eta$ is the path-loss exponent set to 3. The noise power is taken as $-170$ $dBm/Hz$ and a total bandwidth

**Algorithm 1** Proposed algorithm for iterative power allocation and procurement.

```
INIT: $\mathbb{K}^- = \{k \in \mathbb{K}_m,\ \forall m\ :\ r_{m,k}^{min} > 0\}$
INIT: $P_{m,k}^{(u)} = 0,\ P_{m,s}^{(g)} = 0,\ \forall k, s, m$
repeat
  for all users $k \in \mathbb{K}^-$ do
    for all power sources $s \in \mathbb{S}_n, \forall n$ do
      Compute ${P_{m,s}^{(g)}}^{opt} = \arg\max_{P_{m,s}^{(g)}} \mathcal{U}_{m,k}^{(r)} \left(P_{m,s}^{(g)}\right)$
    end for
  end for
  $(m^*, k^*, s^*) = \arg\max_{m,k,s} \mathcal{U}_{m,k}^{(r)} \left({P_{m,s}^{(g)}}^{opt}\right)$
  $n^* = \{n/s \in \mathbb{S}_n\}$
  if $U_{m^*,k^*}^{(r)} \left({P_{m^*,s^*}^{(g)}}^{opt}\right) > 0$ then
    $P_{m^*,k^*}^{(u)} = P_{m^*,k^*}^{(r)} \left({P_{m^*,s^*}^{(g)}}^{opt}\right) + P_{m^*,k^*}^{(u)}$
    ${P_{s^*}^{(g)}}^{max} = {P_{s^*}^{(g)}}^{max} - {P_{m^*,s^*}^{(g)}}^{opt}$
    if $n^* \neq m^*$ then
      ${P_{m^*,n^*}^{(t)}}^{max} = {P_{m^*,n^*}^{(t)}}^{max} - \Psi_{\epsilon_{n^*,s^*}}^{(g)} \left({P_{m^*,s_n^*}^{(g)}}^{opt}\right)$
    end if.
    if $r_{m^*,k^*} \left(P_{m^*,k^*}^{(u)}\right) \geq r_{m^*,k^*}^{min}$ then
      $K^- = K^- - \{k^*\}$
    end if.
  end if.
until $\left\{ {P_s^{(g)}}^{max} = 0, \forall s \text{ OR } U_{m^*,k^*}^{(r)} \left({P_{m^*,s^*}^{(g)}}^{opt}\right) \leq 0 \text{ AND } \mathbb{K}^- = \oslash \right.$
```

TABLE I
SYSTEM PARAMETERS

| Symbol (Unit) | Internal Sources | Main Grid | Exhcange Links |
|---|---|---|---|
| Resistivity : $\rho(\Omega.Km^{-1})$ | 0.1 | 0.2 | 0.1 |
| Transformer loss : $\xi(\%)$ | 0 | 2 | 1 |
| Maximum load : $P^{max}(W)$ | 900 | $\infty$ | 900 |
| Unit power price : $\alpha(\$/kWh)$ | 0 | 0.25 | |

per each BS $B = 10\ MHz$ divided uniformly among the served users. The minimum required throughput rate per user is set to $r_k^{min} = 10\ Mbps$ while the maximum is set to $r_k^{max} = 100\ Mbps$. The unit throughput reward $\kappa_{m,k}$ is set to 0.01$ per $MB$. The BS power consumption parameters are taken from [12] as $P_m^{(0)} = 130\ W$ and $\beta_m = 4.7$. Each micro-grid has one (1) internal renewable source with a random capacity of production (e.g., according to weather conditions) following a normal distribution with average $E[P^{gmax}] = 900\ W$ and standard deviation $\sigma[P^{gmax}] = 100\ W$. In addition, the micro-grids are connected to the main grid assumed with infinite capacity but with relatively high unit power price set to 0.25$ per kWH so that it is used only when renewable is not available. The power loss parameters over the lines are shown in Table I.

In Fig. 2, we present the payoff gain when varying the average and standard deviation of the sources' power capacity. First, we highlight the very close-performance between the proposed algorithm and the optimal solution. Second, we remark the important achieved gain using this approach which justifies its application in practice. In particular, this gain increases for low power availability and high variance. When the average available power is low, the resources become very rare and thus their smart allocation is very important. Among that, exchanging it between the micro-grids to maximize the global reward. Similarly, when the variance of the available power between micro-grids increases, it becomes more important to exchanging it among them in order to compensate the shortage for micro-grids with low power availability.

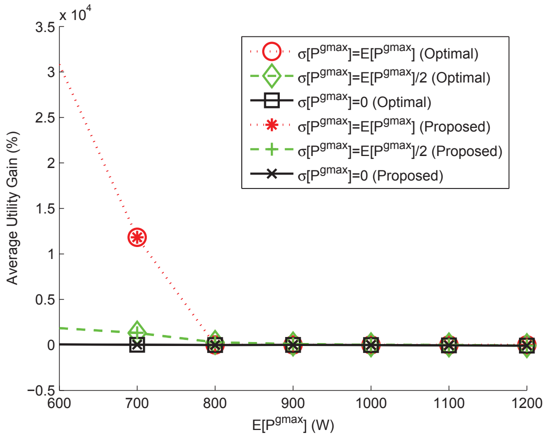

Fig. 2. Utility gain for as function of the variation of the power capacity distribution.

In Fig. 3, we assume a variable unit price for procuring power between the micro-grids. Assuming that the price follows a normal distribution, we show the payoff gain as a function of the unit power price's average and standard deviation. Again, we observe the increase of the payoff gain when the variation of the price increases. Hence, it is more efficient to get power from a neighboring micro-grid, despite of the incurred losses, if its unit price is much lower. On the other hand, when the price decreases, the exchange become inefficient which explains the absence of gains when the average unit price is 0.

## V. CONCLUSION

In this paper, we investigate the optimization of joint power procurement and resource allocation in order to enhance the communication system's performance while reducing the energy usage. While considering cellular communication systems having the ability to produce their energy needs, we aim to get profit of possibility of power exchange between the micro-grids in order to enhance the global payoff and cover the variability of the demand and energy supply. We formulate a global optimization problem and propose a low-cost solution that considers a subspace of the feasibility set. The procurement and allocation decisions are done iteratively among users from the different power sources based on the

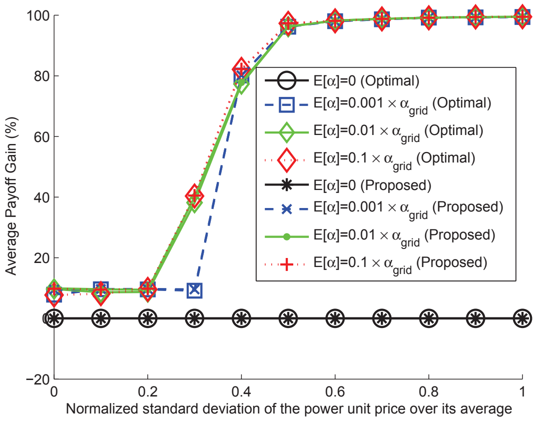

Fig. 3. Utility gain for as function of the variation of the unit power price distribution.

contribution towards the global utility. Simulation results prove the efficiency of the proposed scheme to enhance the global payoff and close-optimality of the proposed algorithm.

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