2014

Power-efficient operation of wireless heterogeneous networks using Smart Grids View Document

Mingyi Hong, *University of Minnesota - Twin Cities*
Hao Zhu, *University of Illinois at Urbana-Champaign*

Power-Efficient Operation of Wireless Heterogeneous Networks using Smart Grids

Mingyi Hong

Dept. of ECE, Univ. of Minnesota
Minneapolis, MN, USA
Email: mhong@umn.edu

Hao Zhu

Dept. of ECE, Univ. of Illinois
Urbana, IL, USA
Email: haozhu@illinois.edu

***Abstract*—In this paper, we consider the power efficient operation of a wireless Heterogeneous Network (HetNet). Reducing the energy consumption is crucial for a successful HetNet deployment, as the increasing number of distributed base stations (BSs) leads to significant economical and environmental concerns. For traditional wireless networks, power efficiency is achieved by designing the transmit strategies in a way that minimal amount of transmit power is achieved within the BS. However, the rapid penetration of renewable energy sources as well as the recent trend of powering the HetNet using smart grids require a fresh look at the well-studied problem. Meanwhile, increasing demand for powering wireless networks also introduces additional operational concerns for the power grid. In this paper, we show how to jointly model these two systems for power efficient operation. We formulate the problem as one that jointly minimizes the power loss of the distribution network as well as the total transmit power in the HetNet. We also show that the resulting problem can be implemented in a distributed manner when the network is divided into multiple zones. Numerical results corroborate several advantageous features of the proposed joint design as compared with the existing HetNet operation method.**

I. Introduction

Heterogenous network (HetNet) has been advocated as a promising architecture for future wireless cellular networks [1]. In a HetNet, a large number of wireless access points or base stations (BSs) are deployed densely in a given region. These BSs can have very different capabilities in terms of total transmit power, the number of transmit antennas, or the availability of the backhaul connection, hence the name of the HetNet.

Albeit the HetNet offers a variety of benefits, such as the flexibility in its deployment and the potential increase of the overall spectrum efficiency, power energy efficiency operations remains a big challenge [2]. It is projected that by 2015, the total number of deployed BSs will reach 50 million. Furthermore, in less than 15 years, the number of BSs may exceed that of the cell phone users [3]. Due to the large amount of BSs that are being added, the wireless access network will soon become a major energy consumer. For example, in a recent white paper compiled by AT&T and University of Melbourne [4], it is reported that by 2015, the wireless access technologies will dominant the power consumption for the wireless cloud – a technology that has rapidly became the driving force in global internet services. Clearly, energy cost will represent a significant portion of the operating expenditure (OPEX) for network operators.

Traditionally, power efficient wireless communication has been tackled in the physical layer via proper power control [5], [6]. For the HetNet, power control itself is not enough anymore, and hence many works have proposed more advanced schemes that combine various upper-layer strategies such as adaptive BS activation to further reduce the energy consumption [7], [8]. Recent trend in HetNet operations is to jointly optimize the wireless network as well as the smart power grid that supports its operations [9]–[16]. This way, it is easier to coordinate the renewable energy sources into the system, therefore much improved energy efficiency can be achieved. Reference [10] suggests to combine the physical layer technique of coordinated multi-point (CoMP) with two-way energy trading. It is shown that the joint design obtains significant cost reduction compared with noncooperative designs. Reference [15] proposes an online strategy that ensures the instantaneous power demand of the wireless networks is matched by using either the finite-capacity battery or the stochastic renewable energy source. Reference [16] also considers a cellular network powered by the smart grid. The CoMP scheme is again used to ensure the quality of service (QoS) of the users, while the BSs together decide on how to procure electricity in the most cost-effective manner.

Most of the above mentioned works consider optimizing the power/energy consumption of the wireless network and balancing such consumption with the supply provided by the grid. Unfortunately they all lack detailed modeling of the underlying power network, in particular the power flow constraints and various operational constraints of the grid. Therefore, it is highly possible that the resulting strategies would induce an infeasible power flow model and may violate the constraints posed by the underlying power networks. Furthermore, the HetNet operations may also introduce unprecedent flow patterns that require the attentions of the power system operator. Hence, the existing strategies developed for the BSs are ignorant of the coupling between the load for supplying the HetNet and the power network physical models. In this paper, we consider the optimization of the energy consumption of the HetNet, which is powered by a distribution power network with a number of renewable sources. We formulate the problem by considering both the QoS constraints of the HetNet as well as the power flow constraints of the grid. The resulting problem can easily include various HetNet design strategies such as dynamic BS activation and clustering. Moreover, we show that the problem can be efficiently solved in a distributed manner by the well-known Alternating Direction Method of Multipliers (ADMM); see e.g., [17]. Numerical results demonstrate several distinctive features of the proposed joint design as compared with the traditional design for the HetNet.

II. System Modeling

A. The Power Grid Model

We consider a wireless HetNet that is powered by a single distribution-type power system. The power system could be a typical distribution feeder serviced by an electric utility, or a small-footprint power grid such as microgrids. To this end, the power system is modeled as an undirectional single branch radial circuit. As illustrated in Fig. 1, the bus 0 only connects the feeder circuit to the main grid, without any directly connected load/generator. In addition, the other buses in the feeder are given by the set $\mathcal{K} := \{1, \ldots, K-1\}$, with $|\mathcal{K}| = K-1$. Each of the bus can be attached to some load and/or some (renewable) power generation source such as photovoltaic (PV) solar panels. Without loss of generality, assume that each bus k is connected to one generation source and one load. Let V_k denote the voltage magnitude per bus k in per unit (p.u.), while P_k and Q_k correspond to the p.u. real and reactive power flowing from bus k to bus $k+1$, respectively. In addition, let p_k and q_k denote the p.u. real and reactive power consumed by load k; and similarly g_k and h_k for the power provided by the generation source per bus k. With the impedance of the line connecting buses k and $k+1$ being $r_k + jx_k$ in Ohms, the linear DistFlow equations are given to model the power network flow as follows [18]

$$P_{k+1} = P_k - p_{k+1} + g_{k+1}, \quad \forall\, k = 0, \cdots, K-1, \tag{1a}$$

$$Q_{k+1} = Q_k - q_{k+1} + h_{k+1}, \quad \forall\, k = 0, \cdots, K-1, \tag{1b}$$

$$V_{k+1} = V_k - \frac{r_k P_k + x_k Q_k}{V_0}, \quad \forall\, k = 0, \cdots, K-1. \tag{1c}$$

$$P_{K-1} = 0,\ Q_{K-1} = 0,\ V_0 = 1 \tag{1d}$$

where the last equations in (1d) correspond to the boundary conditions for the end bus $K-1$ and the feeder bus 0. Operational concerns for power systems further motivate to constrain the power flow model. For simplicity, a voltage regulation constraint is included to ensure

$$1 - \epsilon \le V_k \le 1 + \epsilon, \quad \forall\, k = 1, \cdots, K-1 \tag{2}$$

with ϵ typically taking the value 0.05. The real power loss of the line between bus k to bus $k+1$ is given by

$$l_k = r_k \frac{P_k^2 + Q_k^2}{V_0^2}, \quad \forall\, k = 0, \cdots, K-2. \tag{3}$$

B. The First HetNet Model

Assume that each bus k (except bus 0, which is only connected to the main grid) is connected to a single BS k, and the set of BSs $\mathcal{K} := \{1, ..., K-1\}$ are densely deployed to serve a set of $\mathcal{I}$ users. For simplicity throughout the paper we assume that the BS k is the only load on bus k, but our model can be easily extended to more general cases with other coexisting loads. Assuming that the user-BS association has already been determined, and a BS k serves a subset of users $\mathcal{I}_k \subset \mathcal{I}$. Suppose that each BS has M transmit antennas, and each user has a single receive antenna. A given BS k uses a linear beamformer $\mathbf{v}_{i_k} \in \mathbb{C}^M$ to serve the ith user $i_k \in \mathcal{I}_k$. Let us use $\mathbf{h}^{\ell}_{i_k} \in \mathbb{C}^M$ to denote the channel between BS ℓ and user i_k, and use n_{i_k} to denote the noise plus the additional interference generated by other co-existing systems. Then the aggregated signal received at user i_k is given by

$$y_{i_k} = \underbrace{\mathbf{v}^H_{i_k}\mathbf{h}^k_{i_k}}_{\text{useful signal}} + \underbrace{\sum_{j\neq i, j_k\in\mathcal{I}_k} \mathbf{v}^H_{j_k}\mathbf{h}^k_{i_k}}_{\text{intracell interference}} + \underbrace{\sum_{\ell\neq k, j_\ell\in\mathcal{I}_\ell} \mathbf{v}^H_{j_\ell}\mathbf{h}^\ell_{i_k}}_{\text{intercell interference}} + n_{i_k}. \tag{4}$$

The signal to interference plus noise ratio (SINR) measured at user i_k's receiver can be expressed as

$$\text{SINR}_{i_k} := \frac{\|\mathbf{v}^H_{i_k}\mathbf{h}^k_{i_k}\|^2}{\sigma^2_{i_k} + \sum_{j\neq i, j_k\in\mathcal{I}_k} \|\mathbf{v}^H_{j_k}\mathbf{h}^k_{i_k}\|^2 + \sum_{\ell\neq k, j_\ell\in\mathcal{I}_\ell} \|\mathbf{v}^H_{j_\ell}\mathbf{h}^\ell_{i_k}\|^2}.$$

where $\sigma^2_{i_k}$ denotes the power for n_{i_k}.

The overall network model is illustrated in Fig. 1.

C. The Second HetNet Model

A probably more interesting HetNet model is the one that allows the BSs to cooperate in serving the users, in which way the overall system performance can be significantly improved [19], [20]. Assume that all the BSs in set $\mathcal{K}$ can share the users' messages, and therefore can form a single *virtual BS* to serve each user $i \in \mathcal{I}$. In this case users are no longer associated to a single BS. We use $\mathbf{v}^k_i \in \mathbb{C}^M$ to denote the beamformer used by BS $k \in \mathcal{K}$ to serve user $i \in \mathcal{I}$. Define $\mathbf{v}_i = \left[(\mathbf{v}^1_i)^H, \cdots, (\mathbf{v}^K_i)^H\right]^H \in \mathbb{C}^{MK}$ as user i's *virtual beamformer*. Similarly, define $\mathbf{h}^k_i \in \mathbb{C}^M$ and $\mathbf{h}_i \in \mathbb{C}^{MK}$ as the channel from BS k to user i, and user i's *virtual channel*, respectively. Further define $\mathbf{v}^k = \left[(\mathbf{v}^k_1)^H, \cdots, (\mathbf{v}^k_I)^H\right]^H \in \mathbb{C}^{MI}$ as the collection of beamformers used by BS k to serve all the users.

Then the SINR for user i is given by

$$\text{SINR}_i = \frac{\|\mathbf{h}^H_i \mathbf{v}_i\|^2}{\sum_{j\neq i} \|\mathbf{h}^H_i \mathbf{v}_j\|^2 + \sigma^2_i}. \tag{5}$$

See Fig. 2 for an illustration of the network configuration.

III. Power Efficient HetNet Operation

Our task is to design the wireless HetNet so that it efficiently consumes the power provided by the network while optimally serving the users. Power efficient wireless transmission is a well-studied subject. Traditional approaches such as those

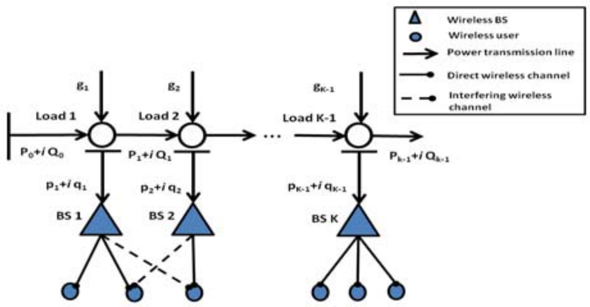

Fig. 1. The first network setup. Each BS serves a given set of users.

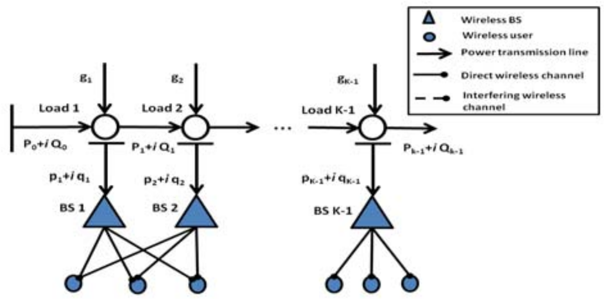

Fig. 2. The second network setup. All the BSs collaborate to serve all the users.

surveyed in [2] mostly aim at designing the transmit schemes that minimize the total transmission power of the wireless system. If the wireless system is viewed as a load in service connected to a larger power system, the notion of *power efficiency* needs to be re-defined. It can no longer be achieved by only considering the wireless transmission side of the problem. Various additional factors such as the losses in the power system as captured by (3), the availability of the renewable power source, the cost of power provisioning, as well as the interplay between the wireless and the power systems need to be taken into consideration. The HetNet architecture adds a further layer of complexity to the problem, as many advanced tasks in the HetNet, such as BS collaboration, user-BS association, should be re-thought by coupling with the underlying power network as well.

To this end, suppose each user i_k has a Quality of Service (QoS) constraint; i.e., it requires that the user received SINR is larger than certain threshold γ_{i_k}. Let p_k denote the power consumed by the entire BS k, and $p_k\eta_k$ correspond to the radiated transmit power consumed by BS k, where $0<\eta_k<1$ is a known constant[1]. Also let $\bar{p}_k$ denote BS k's maximum transmit power. Assume that the power generated by the renewable g_k+jh_k at all buses is given as known. We can formulate the following power efficient beamforming problem for the first type of network

$$\begin{aligned} \min \quad & \sum_{k\in\mathcal{K}} r_k\frac{P_k^2+Q_k^2}{V_0^2}+\lambda\sum_{k\in\mathcal{K}}\sum_{i_k\in\mathcal{I}_k}\|\mathbf{v}_{i_k}\|^2 \\ \text{s.t.} \quad & \mathrm{SINR}_{i_k}\ge\gamma_{i_k},\ \forall\ i_k\in\mathcal{I} \\ & \sum_{i_k\in\mathcal{I}_K}\|\mathbf{v}_{i_k}\|^2\le\eta_k p_k,\ 0\le\eta_k p_k\le\bar{p}_k,\ \forall\ k\in\mathcal{K} \\ & \text{(1a)}-\text{(1d)},\ \text{and (2)}. \end{aligned} \tag{6}$$

where $\gamma_{i_k}\ge 0$ is a given constant modeling the minimum QoS requirement from user i_k. Notice that the first summation term of the objective in (6) is the entire network power loss corresponding to (3). In this formulation, we are interested in minimizing the power demand of the wireless HetNet as well as the cost of delivering the power at the power grid. The latter is measured by the overall loss along the entire distribution network. Here $\lambda>0$ is a constant that trades off these two criteria. Note that constraints (1a)-(1d) model the power flow in the distribution network. Therefore, under the circumstances that the BSs would like to share the energy harvested from the renewable power source (see, e.g., [11], [10], [14], [13]), these equations enforce the underlying physical systems for the power to flow from one location to another.

Although the SINR constraint in (6) is nonconvex, it can be transformed to an equivalent convex second order cone (SOC) constraint, by using a proper phase rotation for each beamformer $\mathbf{v}_{i_k}$ [6]

$$\mathbf{v}_{i_k}^H\mathbf{h}_{i_k}^k\ge\sqrt{\sigma_{i_k}^2+\sum_{j\neq i,j_k\in\mathcal{I}_k}\|\mathbf{v}_{j_k}^H\mathbf{h}_{i_k}^k\|^2+\sum_{\ell\neq k,j_\ell\in\mathcal{I}_\ell}\|\mathbf{v}_{j_\ell}^H\mathbf{h}_{i_k}^\ell\|^2}.$$

Therefore problem (6) is a convex SOC problem.

For the second type of network, besides achieving power efficient operation, we are further interested in either using a small number of BSs to serve a given user k (BS clustering problem, [21]), or shutting down a few BSs (BS activation problem [7]). Both of these strategies help in reducing the total backhaul capacity needed for sharing the users' data messages among the collaborating BSs. The activation strategy can further reduce the power consumption of the entire system; see, e.g., [8]. Both of these problems can be formulated in a unified way by

$$\begin{aligned} \min \quad & \sum_{k\in\mathcal{K}} r_k\frac{P_k^2+Q_k^2}{V_0^2}+\lambda\sum_{i\in\mathcal{I}}\|\mathbf{v}_i\|^2+\mathrm{R}(\mathbf{v}) \\ \text{s.t.} \quad & \mathrm{SINR}_i\ge\gamma_i,\ \forall\ i\in\mathcal{I} \\ & \sum_{i\in\mathcal{I}}\|\mathbf{v}_i^k\|^2\le\eta_k p_k,\ 0\le\eta_k p_k\le\bar{p}_k,\ \forall\ k\in\mathcal{K} \\ & \text{(1a)}-\text{(1d)},\ \text{and (2)} \end{aligned} \tag{7}$$

where the term $R(\mathbf{v})$ in the objective represents the proper penalization terms used to achieve either BS clustering or BS activation. For example, let $\zeta_k>0$ be some constant. Then by using the following mixed ℓ_1/ℓ_2 penalization [7]

$$R(\mathbf{v})=\sum_{k\in\mathcal{K}}\zeta_k\|\mathbf{v}^k\|:=R^{\mathrm{AC}}(\mathbf{v}) \tag{8}$$

[1]Note that here we have made a simplification in which the total power consumed by the BS is assumed to be proportional to its transmitted power. Our model can be easily extended to the one that models part of the BS power consumption as a constant, see e.g., [10].

only a small number of BSs will be activated. Similarly, the following penalization [21]

$$R(\mathbf{v})=\sum_{i\in\mathcal{I}}\zeta_k\sum_{k\in\mathcal{K}}\|\mathbf{v}_i^k\|:=R^{\mathrm{C}}(\mathbf{v}) \tag{9}$$

requires that a few BSs serve each user.

By utilizing a phase rotation on the $\mathbf{v}_i$'s, the QoS constraints in (7) can be transformed into a set of SOC constraints, rendering problem (7) again a convex SOC program.

A. Distributed Implementation

In the previous section, we have formulated the joint wireless and power network optimization problem into two convex programs (6) and (7). These problems can be solved in a centralized manner using off-the-shelf solvers such as CVX [22] to yield globally optimal solutions. In this section we briefly discuss how these problems can be solved in a distributed fashion. We note that distributed implementation can be important for example when the entire network is divided into several autonomous zones, each managed by a local operator.

Our main tool is the well-known Alternating Direction Method of Multipliers (ADMM); see [17] for a survey, and also see [23] for its recent application in power system state estimation. For the ease of presentation, we focus on problem (7) without the nonmooth penalization term $R(\mathbf{v})$. Assume that the microgrid is divided into two zones $\mathcal{K}_1$ and $\mathcal{K}_2$, where $\mathcal{K}_1$ includes the buses $\{1,\cdots,\widehat{k}\}$, and $\mathcal{K}_2$ includes the buses $\{\widehat{k}+1,\cdots,K-1\}$. Let $\mathbf{h}_i^{\mathcal{K}_\ell}$ define the channels from the BSs in $\mathcal{K}_\ell$ to the user i, $\forall\ \ell=1,2$. Define $\mathbf{v}_i^{\mathcal{K}_\ell}$ similarly and let $\mathbf{v}^{\mathcal{K}_1}:=\{\mathbf{v}_i^{\mathcal{K}_1}\}_{i\in\mathcal{I}}$ and $\mathbf{v}^{\mathcal{K}_2}:=\{\mathbf{v}_i^{\mathcal{K}_2}\}_{i\in\mathcal{I}}$. Further introduce a set of auxiliary variables $\boldsymbol{\kappa}:=\{\kappa_{i,j}\}$ as follows

$$\kappa_{i,j}=\mathbf{h}_i^H\mathbf{v}_j=(\mathbf{h}_i^{\mathcal{K}_1})^H\mathbf{v}_j^{\mathcal{K}_1}+(\mathbf{h}_i^{\mathcal{K}_2})^H\mathbf{v}_j^{\mathcal{K}_2}. \tag{10}$$

Then the QoS constraint in problem (7) is given by

$$\kappa_{i,i}\ge\sqrt{\left(\sum_{j\neq i}\kappa_{i,j}+\sigma_i^2\right)\gamma_i},\ \forall\ i\in\mathcal{I}. \tag{11}$$

In this way, we can divide the the design variables for the wireless part into $\mathbf{v}^{\mathcal{K}_1}$ and $\mathbf{v}^{\mathcal{K}_2}$, each of them belonging to a single zone. Moreover, these variables are only coupled by the linear constraints (10).

Similarly, introduce the auxiliary variables $(\hat{P}_{\widehat{k}},\hat{Q}_{\widehat{k}},\hat{V}_{\widehat{k}})$ as follows

$$\hat{P}_{\widehat{k}}=P_{\widehat{k}},\ \hat{Q}_{\widehat{k}}=Q_{\widehat{k}},\ \hat{V}_{\widehat{k}}=V_{\widehat{k}}, \tag{12}$$

where they are used to define the following set of additional flow equations for zone $\mathcal{K}_2$

$$P_{\widehat{k}+1}=\hat{P}_{\widehat{k}}-p_{\widehat{k}+1}+g_{\widehat{k}+1}, \tag{13}$$

$$Q_{\widehat{k}+1}=\hat{Q}_{\widehat{k}}-q_{\widehat{k}+1}+h_{\widehat{k}+1}, \tag{14}$$

$$V_{\widehat{k}+1}=\hat{V}_{\widehat{k}}-\frac{r_{\widehat{k}}\hat{P}_{\widehat{k}}+x_{\widehat{k}}\hat{Q}_{\widehat{k}}}{V_0}. \tag{15}$$

In this way the power flow constraints are separable over the following two disjoint set:

$$\mathbf{x}^{\mathcal{K}_1}:=\{P_k,p_k,q_k,V_k,Q_k\}_{k\in\mathcal{K}_1},$$
$$\mathbf{x}^{\mathcal{K}_2}:=\{P_k,p_k,q_k,V_k,Q_k,\hat{V}_{\widehat{k}},\hat{Q}_{\widehat{k}},\hat{P}_{\widehat{k}}\}_{k\in\mathcal{K}_2},$$

and these two sets of variables are only coupled through the equality constraint (12).

After introducing these additional variables and constraints, we can dualize the coupling equality constraints (10) and (12), and construct the so-called *Augmented Lagrangian function*. To this end, we introduce the set of dual variables $\boldsymbol{\delta}:=\{\delta_{i,j}\}$, one for each equality constraint in (10). We also introduce three dual variables $\boldsymbol{\beta}:=\{\beta_1,\beta_2,\beta_3\}$, one for each equality constraint in (12). Then the *Augmented Lagrangian function* is given by

$$\begin{aligned}&L(\mathbf{x}^{\mathcal{K}_1},\mathbf{x}^{\mathcal{K}_2},\mathbf{v}^{\mathcal{K}_1},\mathbf{v}^{\mathcal{K}_2},\boldsymbol{\kappa};\boldsymbol{\delta},\boldsymbol{\beta})\\&=\sum_{\ell=1,2}\sum_{k\in\mathcal{K}_\ell}\left(r_k\frac{P_k^2+Q_k^2}{V_0^2}+\|\mathbf{v}^k\|^2\right)\\&+\sum_{i,j}\frac{\rho}{2}\left\|\kappa_{i,j}-(\mathbf{h}_i^{\mathcal{K}_1})^H\mathbf{v}_j^{\mathcal{K}_1}-(\mathbf{h}_i^{\mathcal{K}_2})^H\mathbf{v}_j^{\mathcal{K}_2}+\frac{\delta_{i,j}}{\rho}\right\|^2\\&+\frac{\rho}{2}\left(\|\hat{P}_{\widehat{k}}-P_{\widehat{k}}+\frac{\beta_1}{2}\|^2+\|\hat{Q}_{\widehat{k}}-Q_{\widehat{k}}+\frac{\beta_2}{2}\|^2+\|\hat{V}_{\widehat{k}}-V_{\widehat{k}}+\frac{\beta_1}{3}\|^2\right)\end{aligned}$$

Then the ADMM algorithm can be applied, in which different zones take turns in updating their own design variables. We note that the above formulation has *three* primal block variables $(\mathbf{x}^{\mathcal{K}_1},\mathbf{v}^{\mathcal{K}_1})$, $(\mathbf{x}^{\mathcal{K}_2},\mathbf{v}^{\mathcal{K}_2})$ and $\boldsymbol{\kappa}$. Although the traditional ADMM can only handle problems with 2 block variables, recent advance in the literature shows that the multi-block problem can also been handled, by either properly adjusting the stepsizes [24], [25], or by introducing a few more auxiliary variables [26], [27]. The actual implementation is similar to the one introduced in [7]. Due to space limitation, we omit the details.

IV. Numerical Results

In this section we demonstrate the performance of the proposed schemes. We consider a typical radial circuit with a total of 13 buses (K=13), where bus 0 is connected to the main grid. There are 12 lines with the resistance reactance ratio ranging from 2 to 4. The basecase power of the system is given by 1 kWs per unit (p.u.), which will be used to be obtain all the real power terms in p.u.. We choose $\epsilon=0.05$ for the regulation constraint (2). The wireless network is generated using the following setting. We place 12 BSs and up to $I=15$ active users randomly within an area of 250 square meters (representing dense deployment). Each BS has 3 transmit antennas ($M=3$). We model the channel as a Rayleigh fading channel with zero mean and variance $(200/d_i^k)^{3.5}L_i^k$, where d_i^k is the distance between BS k and user i, and $10\log 10(L_i^k)\sim N(0,64)$. We also assume that $\sigma_i^2=-60\text{dbm},\quad\forall i\in\mathcal{I}$. All the simulation results are averaged over 50 channel realizations. The coefficient η_k that models the relationship between the transmitted power and the total consumed power by the BS is given by $\eta_k=0.05$ for all k. The SINR threshold γ_i is also assumed to be the same for all the users, and it is chosen from $\{10, 20, 30\}$dB, depending on different scenarios simulated.

TABLE I
COMPARISON OF THE TOTAL POWER CONSUMED BY THE HETNET (P.U.); HIGH RENEWABLE CASE ($\alpha = 5$)

SINR γ \ λ	0.01	0.1	1
10dB	5.0 (0.31)	2.7 (0.42)	0.22 (0.20)
20dB	9.5 (8.6)	6.8 (9.3)	4.2 (8.0)
30dB	55.3 (45.1)	5.4 (4.3)	5.1 (4.9)

TABLE II
COMPARISON OF THE TOTAL POWER CONSUMED BY THE HETNET (P.U.); LOW RENEWABLE CASE ($\alpha = 1$)

SINR γ \ λ	0.01	0.1	1
10dB	0.96 (0.40)	0.40 (0.39)	0.39 (0.40)
20dB	5.1 (7.7)	3.9 (7.7)	3.52 (7.7)
30dB	7.3 (N/A)	5.4 (N/A)	4.1 (N/A)

We first consider problem (7) without the additional regularization term. The objective is to minimize the power demand of the wireless network plus the loss of the power system. We compare the performance of the proposed grid-coupled power efficient HetNet system with the case of a *stand alone* HetNet that does not account for the interdependency with the grid. For both systems, we assume that there is a renewable energy source associated with each BS, and the amount of power they generate comes from a uniformly random distribution in the interval $[0,\ \alpha]$ p.u. Further, for the stand alone system, the BSs cannot exchange power and each renewable source k is the only power source available to BS k. We consider two cases in which either we have high renewable generation ($\alpha = 5$ p.u.) or low renewable generation ($\alpha = 1$ p.u.). We also vary the tradeoff coefficient λ to demonstrate its impact on the resulting solutions. Intuitively, a smaller λ value motivates to reduce the power loss in the grid, so the total power that flows into the grid should be reduced. In Table I and Table II, we summarize the resulting total power consumed by the HetNet (i.e., $\sum_{k\in\mathcal{K}} p_k$) with or without the grid support, when the tradeoff coefficient λ is increased from 0.01 to 1. The results for the stand alone system are shown using the parenthesis in the tables. First, we observe that generally speaking increasing λ reduces the power consumption of the HetNet. Second, when λ is small and the renewable is more than enough ($\alpha = 5$), the grid supported HetNet tends to consume more power to reduce the flow in the network, hence reducing the power loss. Third, when the QoS requirement is high, the grid supported HetNet often consumes smaller amount of the power than the stand alone HetNet. This makes sense as the grid support HetNet enables the BSs to perform the so-called *energy cooperation* to achieve better efficiency [10]. Moreover, when the QoS requirement is high but there is no sufficient power supply, the stand alone HetHet may fail to support the requested QoS (represented by "N/A" in Table II).

In Fig. 3 – Fig. 4, we show the total power drawn from the main grid as well as the overall loss in the power network. In Fig. 3, negative value means our grid delivers the additional power to the main grid. It is interesting to observe that when $\gamma = \{10, 20\}$ and $\alpha = 1$, our distribution system essentially operates in an island mode with minimum interaction with the main grid. The renewable power generated matches well with the demand from the HetNet, and this induces the least cost in the power system, as seen in Fig. 4.

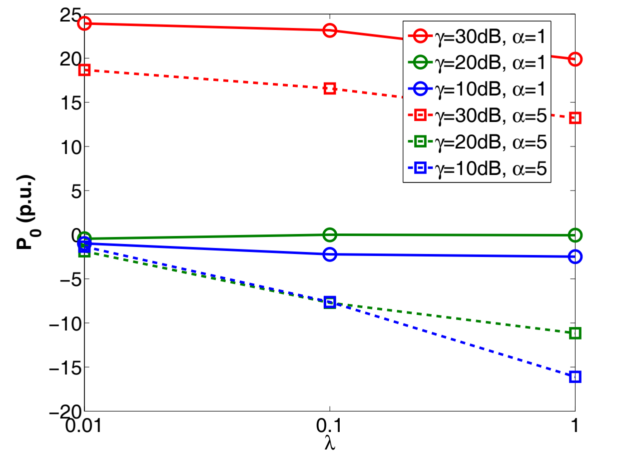

Fig. 3. The total power consumed from the grid (P_0) under different circumstances.

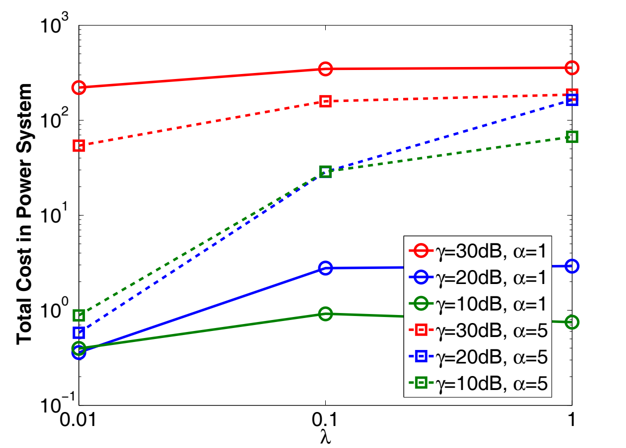

Fig. 4. The total loss in the power system under different circumstances.

In the second experiment we consider problem (7) with the additional requirement to further shutdown a few BSs. Thus $R(\mathbf{v})$ takes the form given in (9). Let us consider the setting that $\alpha = 1$, $\gamma = 10$dB and $I = 5$ (representing the case with low traffic). Fig. 5 shows the number of times each BS gets activated out of a total of 50 trials. It is interesting to observe that the stand alone HetNet essentially randomly activates the BSs, while the grid supported HetNet exhibits distinctive activation pattern. Intuitively this is expected, since allocating the renewable power to the BSs located in the middle of the distribution network is more beneficial in terms of power network loss reduction. In contrast, the stand alone network has no preference as to which BS to activate, because the users as well as the renewable power sources are generated randomly. The message here is that accounting for the power grid to the HetNet can result in the preference of a distinct operational pattern of the HetNet.

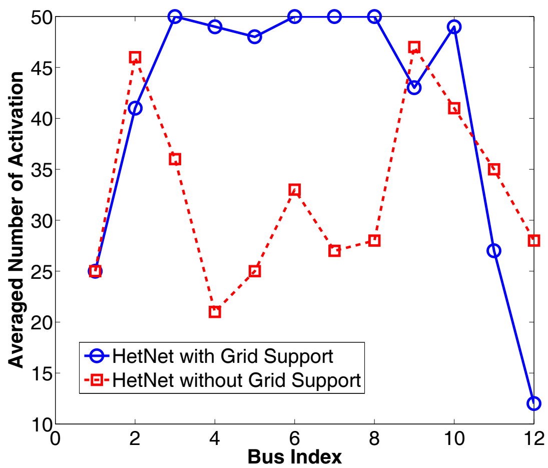

Fig. 5. The number of times different BSs get activated. Total number of trial is 50, $\gamma = 10dB$, $\alpha = 1$, $I = 5$, $K = 13$, $\zeta_k = 10$ for all k.

V. Conclusion

In this work, we consider the power efficient operation of a wireless HetNet supported by a distribution-type power network. The power flow in the network is described by the LinDistFlow model. The BS in the HetNet is assumed to have the ability to cooperate with each other for joint transmission. The overall problem is formulated as the one that minimizes both the cost of the power delivery and the total power consumption of the HetNet. We show that the grid-supported HetNet can significant improve the power efficiency comparing to the stand alone HetNet when the QoS requirement is high. We also show that the inclusion of the power grid to the HetNet can result in different operational pattern compared with the stand alone network. In future, we are interested in analyzing other types of demand response problems for the HetNet with improved physical models. Different topologies of the distribution network as well as more sophisticated flow equations will be considered. More accurate power demand models for the HetNet will also be taken into consideration.

References

[1] A. Damnjanovic, J. Montojo, Y. Wei, T. Ji, T. Luo, M. Vajapeyam, T. Yoo, O. Song, and D. Malladi, "A survey on 3GPP heterogeneous networks," *IEEE Wireless Communications*, vol. 18, pp. 10 –21, 2011.
[2] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green cellular networks: A survey, some research issues and challenges," *IEEE Communications Surveys and Tutorials*, vol. 13, no. 4, pp. 524–540, 2011.
[3] J. Andrews, "Seven ways that Hetnets are a cellular paradigm shift," *IEEE Communications Mag.*, vol. 51, no. 3, pp. 136–144, Mar. 2013.
[4] Bell Labs and University of Melbourne, "The power of wireless cloud," 2013, White paper.
[5] H. Dahrouj and W. Yu, "Coordinated beamforming for multicell multi-antenna wireless systems," *IEEE Transactions on Wireless Communications*, vol. 9, no. 5, pp. 1748–1759, 2010.
[6] A. Wiesel, Y. C. Eldar, and S. Shamai(Shitz), "Linear precoding via conic optimization for fixed MIMO receivers," *IEEE Transactions on Signal Processing*, vol. 54, no. 1, pp. 161–176, 2006.
[7] W.-C. Liao, M. Hong, Y.-F. Liu, and Z.-Q. Luo, "Base station activation and linear transceiver design for optimal resource management in heterogeneous networks," arXiv preprint arXiv:1309.4138.
[8] Y. Cheng, M. Pesavento, and A. Philipp, "Joint network optimization and downlink beamforming for comp transmissions using mixed integer conic programming," *IEEE Transactions on Signal Processing*, vol. 61, no. 16, pp. 3972–3987, Aug. 2013.
[9] R. Zhang Y.-K. Chia, S. Sun, "Energy cooperation in cellular networks with renewable powered base stations," 2013, Preprint, available at arXiv:1301.4786.
[10] J. Xu and R. Zhang, "Cooperative energy trading in comp systems powered by smart grids," 2014, Preprint, available at arXiv:1403.5735.
[11] G. Koutitas and L. Tassiulas, "Smart grid technologies for future radio and data center networks," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 120–128, April 2014.
[12] D. Niyato, Xiao Lu, and Ping Wang, "Adaptive power management for wireless base stations in a smart grid environment," *IEEE Wireless Communications*, vol. 19, no. 6, pp. 44–51, December 2012.
[13] T. Han and N. Ansari, "On optimizing green energy utilization for cellular networks with hybrid energy supplies," *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 3872–3882, August 2013.
[14] K. Huang and V. Li, "On optimizing green energy utilization for cellular networks with hybrid energy supplies," 2014, Preprint, available at arXiv:1404.2074.
[15] J. Leithon, T. J. Lim, and S. Sun, "Online energy management strategies for base stations powered by the smart grid," in *2013 IEEE International Conference on Smart Grid Communications (SmartGridComm)*, Oct 2013, pp. 199–204.
[16] S. Bu, F. R. Yu, Y. Cai, and X. P. Liu, "When the smart grid meets energy-efficient communications: Green wireless cellular networks powered by the smart grid," *IEEE Transactions on Wireless Communications*, vol. 11, no. 8, pp. 3014–3024, August 2012.
[17] S. Boyd, N. Parikh, E. Chu, B. Peleato, and J. Eckstein, "Distributed optimization and statistical learning via the alternating direction method of multipliers," *Foundations and Trends in Machine Learning*, vol. 3, no. 1, pp. 1–122, 2011.
[18] M.E. Baran and F.F. Wu, "Network reconfiguration in distribution systems for loss reduction and load balancing," *IEEE Transactions on Power Delivery*, vol. 4, no. 2, pp. 1401–1407, Apr 1989.
[19] G.J. Foschini, K. Karakayali, and R.A. Valenzuela, "Coordinating multiple antenna cellular networks to achieve enormous spectral efficiency," *IEE Proceedings Communications*, vol. 153, no. 4, pp. 548 – 555, 2006.
[20] D. Gesbert, S. Hanly, H. Huang, S. Shamai, O. Simeone, and W. Yu, "Multi-cell MIMO cooperative networks: A new look at interference," *IEEE Journal on Selected Areas in Communications*, vol. 28, no. 9, pp. 1380 –1408, 2010.
[21] M. Hong, R. Sun, H. Baligh, and Z.-Q. Luo, "Joint base station clustering and beamformer design for partial coordinated transmission in heterogenous networks," *IEEE Journal on Selected Areas in Communications.*, vol. 31, no. 2, pp. 226–240, 2013.
[22] M. Grant and S. Boyd, "CVX: Matlab software for disciplined convex programming, version 1.21," Apr. 2011.
[23] V. Kekatos and G. B. Giannakis, "Distributed robust power system state estimation," *IEEE Trans. on Power Systems*, vol. 28, no. 2, pp. 1617–1626, 2013.
[24] M. Hong and Z.-Q. Luo, "On the linear convergence of the alternating direction method of multipliers," *arXiv preprint arXiv:1208.3922*, 2012, submitted to Mathematical Programming.
[25] M. Hong, X. Wang T.-H. Chang, M. Razaviyayn, S. Ma, and Z.-Q. Luo, "A block successive upper bound minimization method of multipliers for linearly constrained convex optimization," 2013, Preprint, available online arXiv:1401.7079.
[26] X. Wang, M. Hong, S. Ma, and Z.-Q. Luo, "Solving multiple-block separable convex minimization problems using two-block alternating direction method of multipliers," 2013, preprint.
[27] W. Deng and W. Yin, "Parallel multi-block admm with o(1/k) convergence," 2014, preprint.