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Smart Grid and Energy Harvesting for Wireless Communications

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Bachelor Thesis (Telecommunications)

Oct. 25, 2016

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Abstract – Due to the energy consumption is increased to satisfy the demand of wireless communication traffic. The energy cost in cellular network becomes a critical problem. It is necessary and important to find out a solution either energy supply or communication demand side to minimize the operation cost and maximize the quality of service (QoS) in wireless communication. Using renewable energy from the harvesting device such as solar panel and wind turbine become a general solution to save the cost in energy supply side. However, those harvesting device is limit by time and space variance. On the communication demand side, Coordinated multipoint (CoMP) transmission emerge as a technical solution for next wireless generation, the advantage of this approach is that it can extend service coverage, improve spectral diversity and manage inter-cell interference (ICI). Hence, to overcome these challenges and optimize utilities. Joint energy trading in smart grid by implement two-way energy flow and communicate in CoMP system with an energy harvesting device for each base station (BS) can be one feasible solution.

I. Introduction

Since the explosive demand for wireless communication, it will have 50 billion wireless devices in 2020. Hence, it requires building more base stations (BSs) to match a large number of wireless data traffic. The daily energy cost for the cellular network becomes an important portion of operational consumption [2]. Many cellular operators want to reduce the energy expenditure by applying a new solution [2]-[4]. In particular, different allocation designs have

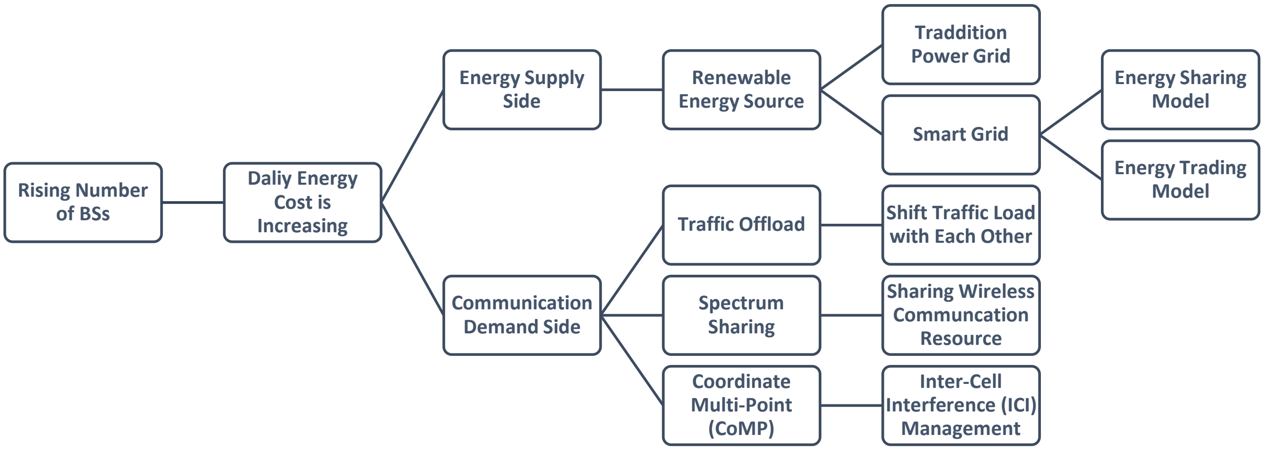

Table 1- A General Flow-Chat for Literature Review the Existing Work and Technical Solution.

been studied for different wireless communication systems[5][6][7][8][9][10]. The existing solutions which can conclude in two main sides: energy supply and communication demand side of cellular networks.

On the energy supply side, because the number of BSs is rising, the electrical consumption for the cellular network contribute some part of the global “carbon footprint” [1]. An environmental and economic concept propose using renewable energy source (RES) from renewable energy harvesting device [12][13][14][15][16]. Those devices can harvest inexpensive and green recycling energy; it is a general solution to reduce the cost even substitute purchasing from the power grid [3]. Furthermore, the cost of the renewable energy harvesting devices are lower than traditional energy from the power grid as well [11][16].

Because both time and space variance limits the renewable energy, the renewable energy is also stochastically and uncontrollable. It is impractical for the BSs only to rely on their own harvesting energy; the BS still need to connect to the power grid to provide a reliable energy in case the harvesting energy exhaustion. Furthermore, the power grid is shifting from traditional grid to smart grid by equipping a large number of advanced smart meters which provides another scheme to saving energy [44][17][18]. The main different between traditional and smart grid is the traditional grid is only permit the electrical energy flow from the power grid to the electricity which is known as one-way energy flow. Unlike the tradition power grid, smart grid deploys a smart meter which enables two-way energy flows between electricity users and power grid[19][20][21]. Hence, the smart meter can implement **energy cooperation**; which means the BS can either trading or sharing in the smart grid.

On the communication demand side, there are several technique solutions proposed in cellular networks for energy consumption saving by different layers [22][23][24][25][26][27][28][29][30][31]. Such as traffic offloading[32], spectrum sharing [33], and coordinated multipoint (CoMP) [37][38][39][40][41][42]. Those technical solutions are fascinating. They allow the BSs not only transfer heavily traffic load to the lightly traffic load but also can share the wireless communication resource to each other [47]. It can save the energy cost and maximize the QoS of the mobile terminals (MTs) at the same time.

On the other hand, severe inter-cell interference (ICI) is rising by the increasing number of BSs. Coordinated multi-point (CoMP) transmission becomes a possible technical solution for next wireless network generation [34][35][36][37][45]. The basic theory is to allow multiple BSs to cooperate and service multiple mobile users as a CoMP cluster. This cluster cooperative communication in same time-frequency resources to avoid the inter-cell interference.

This conventional energy saving solution is not effective in cellular network by taking the advantage of energy supply and communication demand side[46]. Hence, it is necessary to combine the advanced technique solution on both energy supply and communication demand side[48][49][50][51][53]. Thus, the feasible solution is **joint the energy trading and communication in CoMP system with an energy harvesting device in each base station**. In the next section, We will explain the different between energy trading and energy sharing, then describe the superiority for choosing energy trading model in energy cooperation.

II. Energy Cooperation

Energy Cooperation defines as the BS implement two-way trading or sharing to avoid the redundant harvesting renewable energy waste; it is one of the cost saving solutions on the supply side. However, it is too complex for the power grid directly to deal with all the BSs. An aggregator is proposed to complete the energy trading or sharing which can connect a finite number BSs into a cluster. The aggregator can be treat as an intermediary party which is an assistance between the power grid and the BSs [43].

A. Energy Trading in Aggregator

In the energy trading mode, the BS decides purchasing or selling the harvested energy to the power grid by the aggregator implement the two-way energy trading. If BS has enough or even excess harvesting energy, the aggregator can assist BS selling its extra energy to the power grid; Conversely, if BS lacks harvesting energy, then the aggregator can help the BS buying the energy from the power grid. The aggregator can gain some profit by correctly decide the energy purchasing or selling between the BSs and Power Grid.

B. Energy Sharing in Aggregator

In the energy sharing mode, it is another method to achieve the energy cooperation. It allows the finite number of BSs as a cluster sharing the extra harvesting energy to other BSs short of energy. BSs can take or inject from or to the aggregator. To implement that, the BSs require signing a contract with the aggregator. The service charge in the contract becomes the profit for the aggregator to assist this energy sharing.

There is an existing case study have a simulation with two BSs with renewable energy supply; one BS harvests more energy than the other one which can cause the energy trading or sharing [33]:

	BS 1 Harvesting Energy	BS 2 Harvesting Energy	BS 1 Energy Cost	BS 2 Energy Cost	Total Energy Cost
Energy Cooperation via Energy Trading in Aggregator	**4.14**	**8.36**	**4.14**	**18.28**	**10.51**
Energy Cooperation via Energy Sharing in Aggregator	**4.14**	**8.36**	**4.14**	**18.28**	**10.03**

Table 2 - Energy Cost for Energy Trading and Sharing in Aggregator[33]

Obviously, energy sharing in aggregator can save more energy. If we only consider on the energy layer, energy sharing is a good alternative. Since the total energy cost is slightly different which can be negligible. Once we consider the economic layer, Energy Trading model will be better. Since we can sell the redundant energy to the power grid to optimize the smart grid capability. The most important reason is **the cellular operator can obtain some profit from selling the energy to the power grid** which is the biggest advantage compared with the energy sharing in the aggregator.

The rest of this article, We introduce our system model first, then present the problem formulation for joint energy trading and communication in the CoMP system.

III. System Model

For the system model, we consider a cluster CoMP system with $N > 0$ base stations, The BSs cooperative send the message to the K mobile terminals (MTs). The BSs and MTs is denoted as $\mathcal{N} = \{1,2,\dots,N\}$ and $\mathcal{K} = \{1,2,\dots,K\}$. Assume that each base station will have one or two energy harvesting device which can be wind-turbines and/or solar panel. The smart meter is able to join energy harvesting device and power grid which can implement the two-way energy trading. It is also assumed that there is a central processor for each CoMP cluster which is not only manage the energy trading but also collect the cooperative communication data. To implement that the central processor need to collect not only energy information but also communication information which is the energy harvesting rate and the energy selling or buying price and the transmit message and the channel state information(CSI) [55][56][57][58]. An example of $N = 2$ BSs in CoMP system is shown in Figure 1:

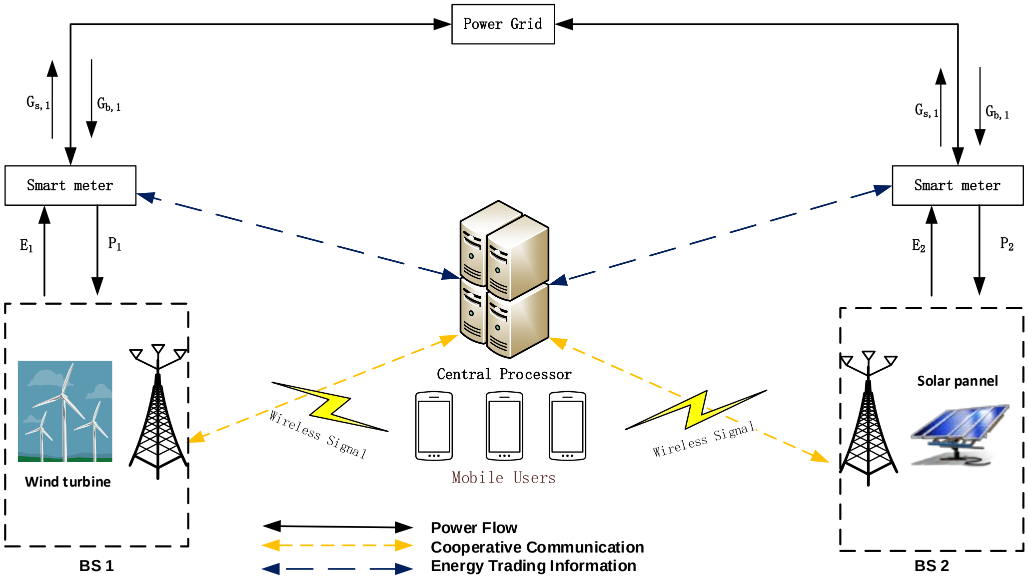

Figure 1 - An example of a CoMP system with two BSs equipped with energy harvesting devices, where smart meters implement the two-way energy trading with the power grid.

Next, I will explain the constraints for both energy trading and consumption model and CoMP system transmission model. Then present the objective function and the constraint set in the end.

A. Energy trading and consumption model

As the system model provide, each BS provides energy harvesting devices which connect to the power grid by a smart meter which can implement the energy trading. The amount of the energy harvest at BS i is denoted by $E_i \geq 0$. The purchasing energy from power grid to BS is denote as $G_{b,i} \geq 0$ and the selling energy from BS i to power grid is denote as $G_{s,i} \geq 0$. Hence the totally energy available at BS i as

$$E_i + (G_{b,i} - G_{s,i})\eta, \quad \forall i \in \mathcal{N} \qquad (1)$$

Note that η is the efficiency for the power transmission line which is assumed as a constant value.

While the BS i is trading with power grid, the selling or buying price is defined as $\alpha_{s,i}$ and $\alpha_{b,i}$. Therefore, the net energy consumption for BS i is:

$$C_i = \alpha_{b,i} G_{b,i} - \alpha_{s,i} G_{s,i}, i \in \mathcal{N} \tag{2}$$

P_i defines the total power consumption at each BS i is, it can be defined as two part: The transmission power $P_{t,i} \geq 0$, and non-transmission power can treat as a constant value $P_{c,i} \geq 0$. Therefore, total power expend at BS i must larger than normal operation energy and the formulate is

$$P_i = P_{t,i} + P_{c,i} \leq E_i + \left(G_{b,i} - G_{s,i}\right)\eta, \forall i \in \mathcal{N} \tag{3}$$

$$G_{b,i} \geq 0, G_{s,i} \geq 0, \forall i \in \mathcal{N} \tag{4}$$

Therefore, there are the first and secondly constraints in energy trading and consumption model.

B. Communication in CoMP system

In the beginning, it is required to denote the channel vector from BS i to MT k as $h_{i,k}$ and let $h_k = [h_{1,k}^T, \dots, h_{N,k}^T]^T$. Consider linear transmit beamforming is applied at the BSs, the signal transmitted to user k is:

$$q_k = \omega_k s_k \tag{5}$$

s_k is the information signal for MT k and its relative beamforming vector across the N BSs is denoted as ω_k. It can be assumed that s_k is a complex random variable with zero mean and unite variance. Therefore, the receive signal y_k at MT k is:

$$y_k = h_k^H q_k + \sum_{l \in \mathcal{K}, l \neq \mathcal{K}} h_k^H q_l + n_k, k \in \mathcal{K} \tag{6}$$

$h_k^H q_k$ is the desired signal and $\sum_{l \in \mathcal{K}, l \neq \mathcal{K}} h_k^H q_l$ is the inter-user interference form the same cluster. n_k is additive noise which might include the downlink interference from other BSs outside the cluster. It is assumed that additive noise n_k is independent circularly symmetric complex Gaussian(CSCG) which is a random variable with zero mean and variance σ_k^2.

Hence, signal-to-interference-plus-noise ratio (SINR) for user k is:

$$\mathrm{SINR}(\{\omega_k\}) = \frac{|h_k^H \omega_k|^2}{\sum_{l\in\mathcal{K},l\neq k} |h_k^H \omega_k|^2 + \sigma_k^2}, k \in \mathcal{K} \tag{7}$$

However, it is in high probability that channel state information vector $h_k$is imprecisely available in practice. According to past channel and measurement. An additive error model: $h_k = \hat{h}_k + \delta_k$ is required, where $\hat{h}_k$ is the actually channel and the range for the uncertainty is bounded by a spherical region [51][52]:

$$\mathcal{H}_k := \left\{\hat{h}_k + \delta_k \middle| \|\delta_k\| \leq \epsilon_k\right\}, \forall k \tag{8}$$

Where ϵ_k is defined the region of $\mathcal{H}_k$, hence for the worst case $\widetilde{\mathrm{SINR}}_K$ can be define as:

$$\widetilde{\mathrm{SINR}}_K(\{\omega_k\}) = \min_{\hat{h}_k \in \mathcal{H}_k} \frac{|h_k^H \omega_k|^2}{\sum_{l\in\mathcal{K},l\neq k} |h_k^H \omega_k|^2 + \sigma_k^2}, k \in \mathcal{K} \tag{9}$$

For satisfying the quality of service (QoS), the third constraint is specified by a minimum $\widetilde{\mathrm{SINR}}_K$requirement γ_k for MT k which is express as:

$$\widetilde{\mathrm{SINR}}_K(\{\omega_k\}) \geq \gamma_k, \forall k \in \mathcal{K} \tag{10}$$

C. Objective function and constraint statement

Our purpose is to minimize the energy cost; it is designed to joint energy trading and communication in CoMP system which is buying $\{G_{b,i}\}$ or selling $\{G_{s,i}\}$ energy to the power grid and optimize the cooperative transmit beamforming vector$\{\omega_k\}$. It is also required to satisfy those constrains at the same time. Hence the formulation for objective function and constrain statement can be summary in to the problem formulation:

Objective function:

$$\min_{\{\omega_k\},\{G_{b,i}\},\{G_{s,i}\}} \sum_{i\in\mathcal{N}} \left(\alpha_{b,i} G_{b,i} - \alpha_{s,i} G_{s,i}\right)\eta \tag{11}$$

Constraint set:

I. $P_i = P_{t,i} + P_{c,i} \leq E_i + \left(G_{b,i} - G_{s,i}\right)\eta, \forall i \in \mathcal{N},$ (12)

II. $$G_{b,i} \geq 0, G_{s,i} \geq 0, \forall i \in \mathcal{N}, \tag{13}$$

III. $$\widetilde{\mathrm{SINR}}_K(\{\omega_k\}) = \min_{h_k \in \mathcal{H}_k} \frac{|h_k^H \omega_k|^2}{\sum_{l \in \mathcal{K}, l \neq k} |h_k^H \omega_l|^2 + \sigma_k^2} \geq \gamma_k, \forall k \in \mathcal{K}. \tag{14}$$

It is a non-convex optimization problem with infinitely many constraints; it is the difficulties of the problem formulation. In general, there is no systematic approach for solving non-convex optimization problems efficiently. In extreme cases, brute force search method is required to find the globally optimal solution which results in exponential computational complexity. As a result, a computational efficient method is needed. In the work, we plan to adopt S-Procedure and Semi-Definite Program (SDP) to handle the difficulties[59][60][61][62].

IV. Optimal Solution

A. Convex Reformulation

Expect for constraint set (14), the reset two constraints are convex. By the definition of $\mathcal{H}_k$ and $\widetilde{\mathrm{SINR}}_K$, the constraint set (14) can rewrite as:

$$\frac{|h_k^H \omega_k|^2}{\gamma_k} \geq \sum_{l \in \mathcal{K}, l \neq k} |h_k^H \omega_l|^2 + \sigma_k^2 \tag{15}$$

Move all the term into LHS:

$$\frac{|h_k^H \omega_k|^2}{\gamma_k} - \sum_{l \in \mathcal{K}, l \neq k} |h_k^H \omega_l|^2 - \sigma_k^2 \geq 0 \tag{16}$$

Set $F_k(\delta_k) \geq 0$ for all δ_k with $\delta_k^H \delta_k \leq (\epsilon_k)^2$;

Then,using $h_k = \hat{h}_k + \delta_k$:

$$F_k(\delta_k) = \left(\hat{h}_k + \delta_k\right)^H \left[\frac{\omega_k \omega_k^H}{\gamma_k} - \sum_{l \in \mathcal{K}, l \neq k} \omega_l \omega_l^H\right] \left(\hat{h}_k + \delta_k\right) - \sigma_k^2 \geq 0 \tag{17}$$

S-procedure: Let A, B be $\mathrm{n} \times \mathrm{n}$ Hermitian matrices, $\mathrm{c} \in \mathbb{C}^n$ and $\mathrm{d} \in \mathbb{R}$ for the interior-point condition holds, there exists an $\bar{\mathrm{x}}$ which is $\bar{\mathrm{x}}^{\mathrm{H}}\mathrm{B}\bar{\mathrm{x}} < 1$ and following the equivalent:

$$x^H A x + c^H x + x^H c + d \geq 0, \mathrm{x} \in \mathbb{C}^n, \bar{\mathrm{x}}^{\mathrm{H}}\mathrm{B}\bar{\mathrm{x}} < 1 \tag{18}$$

There are exist a $v \geq 0$ such as:

$$\begin{pmatrix} A + vB & c \\ c^H & d - v \end{pmatrix} \geq 0 \tag{19}$$

Let $X_k = \omega_k \omega_k^H \in \mathbb{C}^{MI \times MI}$ with that $X_k \geq 0 \,\&\, \mathrm{rank}(X_k) = 1$, by using S-procedure, equation (17) can transformed into equation (19) now.

First, defineY_k as:

$$Y_k = \frac{\omega_k \omega_k^H}{\gamma_k} - \sum_{l \in \mathcal{K}, l \neq k} \omega_l \omega_l^H = \frac{1}{\gamma_k} X_k - \sum_{l \in \mathcal{K}, l \neq k} X_l \tag{20}$$

Then, expand $F_k(\delta_k)$ and format as (18):

$$F_k(\delta_k) = \left(\hat{h}_k + \delta_k\right)^H Y_k \left(\hat{h}_k + \delta_k\right) - \sigma_k^2 \geq 0$$

$$F_k(\delta_k) = \left(\hat{h}_k^H Y_k + \delta_k^H Y_k\right)\left(\hat{h}_k + \delta_k\right) - \sigma_k^2 \geq 0$$

$$F_k(\delta_k) = \hat{h}_k^H Y_k \hat{h}_k + \hat{h}_k^H Y_k \delta_k + \delta_k^H Y_k \hat{h}_k + \delta_k^H Y_k \delta_k - \sigma_k^2 \geq 0 \tag{21}$$

Assume, $\mathrm{x} = \delta_k, \mathrm{A} = Y_k, c = Y_k \hat{h}_k$, then (19) can rewrite as:

$$\Gamma_k = \begin{pmatrix} Y_k + \tau_k I & Y_k \hat{h}_k \\ \hat{h}_k^H Y_k^H & \hat{h}_k^H Y_k \hat{h}_k - \sigma_k^2 - \tau_k (\epsilon_k)^2 \end{pmatrix} \geq 0, \tau_k \geq 0 \tag{22}$$

With auxiliary variables $\tau_k \geq 0$ and dropping rank constraints $\mathrm{rank}(X_k) = 1$, we can rewrite our problem formulation as:

Objective function:

$$\min_{\{X_k\},\{G_{b,i}\},\{G_{s,i}\}} \sum_{i \in \mathcal{N}} \left(\alpha_{b,i} G_{b,i} - \alpha_{s,i} G_{s,i}\right)\eta \tag{23}$$

New constraint set:

$$P_i = P_{t,i} + P_{c,i} \leq E_i + \left(G_{b,i} - G_{s,i}\right)\eta, \forall i \in \mathcal{N},$$
$$G_{b,i} \geq 0, G_{s,i} \geq 0, \forall i \in \mathcal{N},$$
$$\Gamma_k \geq 0, \tau_k \geq 0, X_k \geq 0, \forall k \in \mathcal{K} \qquad (24)$$

Now the $\widetilde{\mathrm{SINR}}_K$ constraint (14) become a convex SDP constraint in (24). Because the objective function is convex, then the program formulation of the new constrain set is convex as well now. The part of SDP relaxation follows a similar approach as the part for theorem 1 in[63] .

V. Numerical Test

In this section, we provide simulation result to prove performance gain for our design which is joint the energy trading and communication in CoMP system. Our proposed optimization design compares with equal power allocation with separate communication and energy trading system. The Matlab-based modeling package CVX 2.1 are used to simulate and solve the optimization problems[64].

In the simulation, we assume a three BSs as a cluster $\mathrm{N} = 3$, each BS has variable transmit antennas which depend on the demand for the test result. The number of the MTs is $\mathrm{K} = 8$ which is randomly inside the cluster. Assume BS1 and BS2 are equipped solar panel and wind turbine energy harvesting device BS3 is deployed both of this two harvesting device. There is two simulation result to proof the performance gain between our optimization design and tradition wireless communication system without energy trading model. By adjusting the number of antennas in each BS, the energy consumption rate can display as Fig. 2.

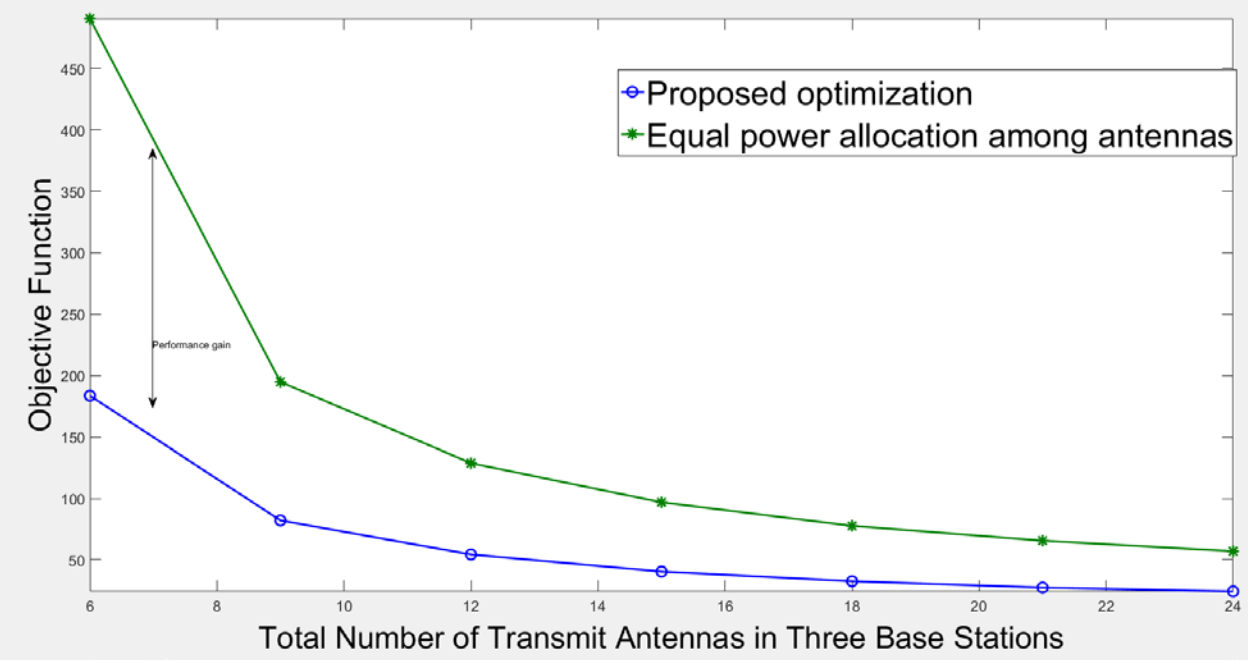

Figure 2 - Comparing with Proposed optimization and Equal Power Allocation Among for Total Energy Cost of Transmit Antennas in Three Base Station

Due to the power efficiency, the total energy cost reduces with more antennas in each BS. Therefore, when the total number of transmit antennas increase will reduce the total energy consumption. The distance between the Proposed optimization and the equal power allocation among antennas is show as the performance gain in Fig.2 which is the among of energy can be saved in a simple cluster with 3 BSs.

The other simulation result presents the normalized maximum channel estimation error improvement. In theory, higher channel estimation error required more energy for QoS and satisfy the SINR requirement. The amount of total energy cost save in the three BSs cluster is display in Fig. 3. The two lines distance is the performance gain between our design and the equal power allocation.

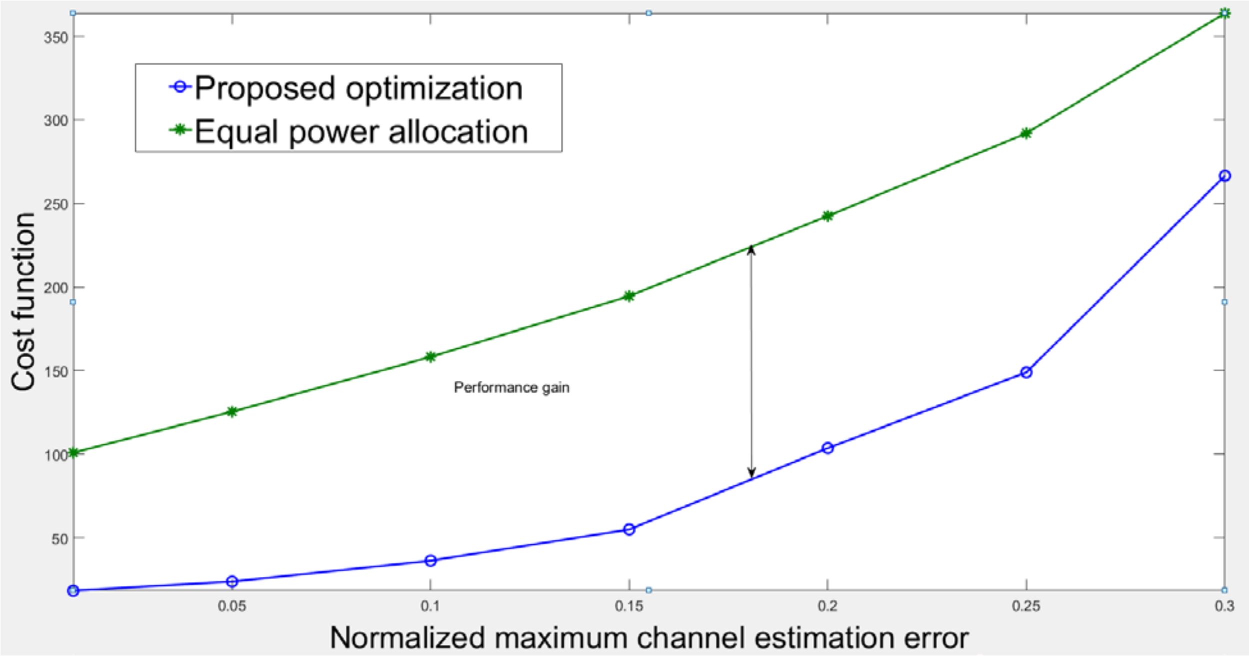

Figure 3 - Comparing with Proposed optimization and Equal Power Allocation Among for Normalized Maximum Channel Estimation Error

VI. Conclusion

In this article, due to the energy consumption is increased to satisfy the demand of wireless communication traffic. Many cellular operators want to reduce the energy cost and maximize QoS of MTs. However, it is no more optimize by taking the advantage separately on energy supply and communication demand side. After introducing the benefit for energy trading model in smart grid, we propose a feasible solution that joint energy trading and communication in CoMP system with one or more energy harvesting device in each base for saving the energy cost. Then we design our system model and problem formulation. By implement S-procedure and Semi-Definite Program (SDP), we rewrite our problem formulation without any non-convex constraint and simulate the result by Matlab with CVS. The simulation result proves that the conventional approach of minimizing the total power cost in wireless communication system is no more optimal. It is necessary to combine the energy supply and communication demand side to achieve the minimal sum-energy consumption.

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