Energy Efficient Radio Resource Management in a Coordinated Multi-Cell Distributed Antenna System

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***Abstract*—As well as the demand for higher data rates goes on, the rising energy costs and environmental concerns have also led researchers to increase energy efficiency in terms of bits-per-Joule. Cooperative communications with low power nodes, switching off under-utilized cells due to low traffic load and energy efficient radio resource management are some of the energy saving methods.**

It is observed that the conventional energy efficiency expression, which is defined as the ratio of the data rate to the total transmission power, can limit the system throughput significantly. In this paper, we introduce a novel energy efficiency expression which provides a trade-off between sum-rate maximization and total transmission power minimization in the network. A coordinated multi-cell distributed antenna system is considered and two energy efficient radio resource management schemes are investigated; either ports can be switched on and off or their transmission power can be adjusted in order to maximize energy efficiency. It is demonstrated that the proposed expression offers significant increase in data rate while keeping total transmission power low. The proposed and the traditional energy efficiency methods asymptotically converge when trade-off effect diminishes, i.e., transmission power minimization takes the full priority.

***Index Terms* - Distributed antenna systems, CoMP, HetNets, port selection, radio resource management, energy efficiency, particle swarm optimization.** [1]

I. INTRODUCTION

There has been an ever increasing demand for data rate and coverage in recent years and this trend is expected to continue. Traditional interference avoidance techniques, which reuse frequency and time to mitigate interference, utilize spectrum inefficiently and can be inadequate to meet the demand for higher data rates. Furthermore, SINR degradation due to signal attenuation and interference from other cells for cell edge users can be considered as a coverage issue. The techniques which have been used in the last decades may not be sufficient to solve all these issues simultaneously. Along with the interference mitigation methods, cooperative transmission leading to coordinated multi-point (CoMP) [1], a promising technique for upcoming LTE-A standard releases [2], will play an important role on future communications especially in heterogeneous networks (HetNets) [3], with the deployment of low power nodes, i.e., pico-, femto-cells and remote radio heads (called ports in LTE-A terminology).

The rising energy costs and environmental concerns have led researchers to save energy, addressing a new research area called green communications. Various energy saving schemes have been proposed to reduce the energy consumption and to design green cellular networks. One of the energy aware concepts in cellular networks is the cell switch off technique in which the number of active cells in the network is reduced during the periods when they are under-utilized due to low traffic load. Authors in [4] characterized the amount of the energy that can be possibly saved considering regular cellular topologies and in [5] it was demonstrated that the combination of CoMP and switch off technique yields further energy saving enhancements in comparison to the traditional switch off techniques. Authors in [6], [7] emphasized energy efficient resource allocation schemes in wireless OFDMA systems by maximizing the energy-efficiency (EE) in terms of bits-per-Joule rather than maximizing the data rate only. Authors in [8], [9] obtained an energy efficient power allocation algorithm to maximize EE in distributed antenna systems (DAS) and used the weighted sum method in multi-criteria optimization to investigate the trade-off between spectral- and energy efficiency under the constraints of the overall transmission power of each port and proportional fairness in data rates. Detailed surveys about energy efficient architectures, EE metric, and energy saving schemes have been presented in [10] and [11]. Energy efficiency of various CoMP techniques is studied in [12], [13] and in [14], CoMP system has been idealized by assuming as a DAS with cooperative processing and a framework for energy efficiency analysis of the system has been introduced.

A downlink CoMP scenario, where ports are utilized to form a distributed antenna system is investigated in [15]. Their goal is to maximize the minimum SINR among all users in the network by choosing the best port settings. They tackle this problem by switching the ports on/off, i.e., selecting the best combination of ports which transmit at a fixed power (e.g., $P_{\max}$) and switching off the others. In [16], this scheme was named as Binary Power Management (BPM) and the Continuous Power Management (CPM) strategy was introduced where ports can transmit at a power level in the interval $[0, P_{\max}]$ rather than $\{0, P_{\max}\}$ as in BPM. It was assumed that inter-user interference in a cell is eliminated by assigning the resource blocks (RBs) to the users of the cell in an orthogonal fashion, i.e., a RB can be used by only one user in a cell, however, inter-cell interference still exists since the user accesses the same RB in other cells. To simplify the formulation and demonstration, transmission over a single RB, i.e., a single user per cell, was considered. The problem to be optimized was multimodal. Therefore, rather than gradient based algorithms which may get stuck in local minima, it was proposed to use an evolutionary algorithm based on Particle Swarm Optimization (PSO) [17].

Neither of the problems in [15], [16] was handled in an energy-efficient manner. In this paper, we consider a downlink CoMP network scenario similar to [16] including intercell interference, but here we focus on energy-efficient resource allocation. It is observed that optimization of the traditional energy efficiency expression which is defined as the sum-rate over total transmission power, may achieve lower transmission power levels however it may also yield lower data rates to satify certain QoS criteria. We introduce a novel energy efficiency expression which provides a trade-off between sum-rate and transmission power. By using this trade-off, all operation states from sum-rate maximization only to transmission power minimization only can be investigated. We find that a slight disturbance of the traditional definition of energy efficiency may result in significant increase in the data rate at the expense of a tolerable increase in the tranmission power.

The paper is organized as follows: Section II describes the system model. Simulation results are provided in Section III and Section IV concludes the paper.

II. SYSTEM MODEL

Consider the downlink scenario depicted in Fig. 1, where there are M cells, and each cell contains L distributed single-antenna ports connected to the network through high speed connection, giving $M \times L$ ports in total. It is assumed that the transmission power of each port can be adjusted independently. Resource management throughout the network is conducted by a central network entity. In this paper, we focus on finding the solution of the problem over a particular RB. At most one user is allowed to access this RB within each cell, hence for an M cell network, M users are considered. A user can communicate with the ports in its dedicated cell, whereas the signals from other cells are considered as interference.

Let x_m be the information signal to be transmitted to the user in the m-th cell, where $E\{x_m x_n\} = 1$ if $m = n$, and zero otherwise. The complex-valued coefficient h_{lnm} represents the channel gain between the l-th port of the n-th cell and the UE in the m-th cell for $l = 1, ..., L$ and $m, n = 1, ..., M$. The zero mean circularly symmetric additive white Gaussian noise with variance σ_η^2 for the UE in the m-th cell is denoted by η_m. Network-wide, each port has a peak power limit given by $P_{\max}$ and the transmission power for the l-th port in the m-th cell is controlled with the power coefficients $\alpha_{lm} \epsilon \{0, 1\}$ for BPM, and $\alpha_{lm} \epsilon [0, 1]$ for CPM. Furthermore, let w_{lm} be the complex beamsteering coefficient for the l-th port in the m-th cell. Then the received signal of the UE in the m-th cell can be written as

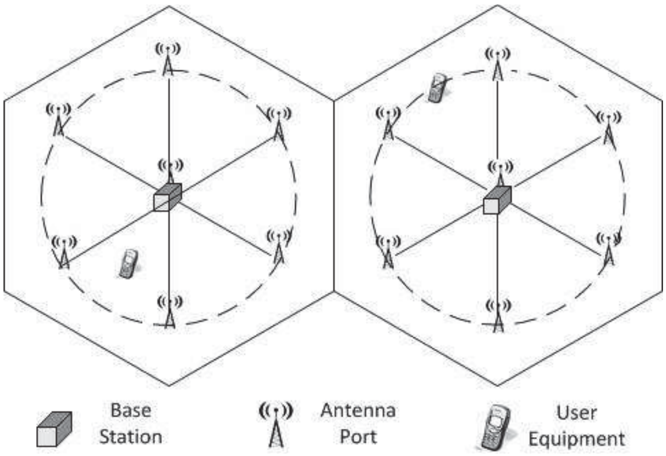

Fig. 1: A two cell network with $L = 7$ distributed antennas per cell.

$$\begin{aligned} y_m = \quad & \sum_{l=1}^{L} \sqrt{\alpha_{lm} P_{\max}} h_{lmm} w_{lm} x_m + \\ & \sum_{n=1, n \neq m}^{M} \sum_{l=1}^{L} \sqrt{\alpha_{ln} P_{\max}} h_{lnm} w_{ln} x_n + \eta_m, \ \forall_m. \end{aligned} \tag{1}$$

The term in the first line provides the signal intended to the user in the m-th cell whereas the second line contains the interference term from the other cells and also noise.

Eventually, the corresponding SINR for the UE in the m-th cell can be expressed as

$$\begin{aligned} & SINR_m(\alpha, \mathbf{w}) = \\ & \frac{\left| \sum_{l=1}^{L} \sqrt{\alpha_{lm} P_{\max}} h_{lmm} w_{lm} \right|^2}{\sigma_\eta^2 + \sum_{n=1, n \neq m}^{M} \left| \sum_{l=1}^{L} \sqrt{\alpha_{ln} P_{\max}} h_{lnm} w_{ln} \right|^2}, \ \forall m, \end{aligned} \tag{2}$$

where the vectors α and $\mathbf{w}$ represent the set of power coefficients (α_{lm}) and the set of beam steering coefficients (w_{lm}), respectively. Eventually, the data rate of the user in the m-th cell is

$$R_m(\alpha, \mathbf{w}) = \log_2(1 + SINR_m(\alpha, \mathbf{w})), \ \forall m, \tag{3}$$

and the sum-rate over the network is given by $R(\alpha, \mathbf{w}) = \sum_{m=1}^{M} R_m(\alpha, \mathbf{w})$.

Maximizing the sum rate only may result in energy inefficiency, i.e., under certain conditions, little gain can be obtained in data rate at the expense of excessive power dissipation. Maximizing the energy efficiency expression [6],

$$EE(\alpha, \mathbf{w}) = \frac{R(\alpha, \mathbf{w})}{P_T(\alpha)} = \frac{\sum_{m=1}^{M} R_m(\alpha, \mathbf{w})}{P_{\max} \sum_{m=1}^{M} \sum_{l=1}^{L} \alpha_{lm}}, \tag{4}$$

can be a solution to this issue. Here, $P_T(\alpha) = P_{\max} \sum_{m=1}^{M} \sum_{l=1}^{L} \alpha_{lm}$ is the total transmission power required to achieve the sum-rate $R(\alpha, \mathbf{w})$.

Although maximizing (4) may yield a low total power level as desired due to energy efficiency, the sum-rate may also be too conservative to satisfy certain QoS conditions. Disturbing the value of (4) slightly, i.e., increasing the total power slightly may yield a significant increase in the sum rate. Therefore, we propose to modify the cost function of the problem to include a trade-off between sum rate maximization and total power level minimization, i.e.,

$$\mu(\alpha, \mathbf{w}) = \frac{R(\alpha, \mathbf{w})}{1 + cP_T(\alpha)} = \frac{R(\alpha, \mathbf{w})}{1 + c_p \sum_{m=1}^{M} \sum_{l=1}^{L} \alpha_{lm}}. \quad (5)$$

Here, the scalar $c \in \mathbb{R}_+$is a trade-off parameter. As $c \rightarrow 0$, the problem becomes a sum rate maximization problem with no intention to minimize the total transmission power. Similarly, as $c \rightarrow \infty$, minimization of the total transmission power becomes more dominant. Note that, in order to remove the effect of P_{max} on the analysis, in the rest of the paper we consider $c_p = cP_{max}$ as the trade-off control parameter, instead of the scalar c.

It can be seen from (5) that the variables of the problem are α_{lm} and w_{lm} which represent power and beamsteering coefficients, respectively. Then, for the Binary Power Management (BPM) scenario, the problem can be formulated as

$$\begin{array}{ll} \max\limits_{\alpha,\mathbf{w}} & \mu(\alpha, \mathbf{w}) \\ \text{s.t.} & \alpha_{lm} \in \{0,1\}, \forall l, m, \\ & |w_{lm}| = 1, \forall l, m, \\ & SINR_m(\alpha, \mathbf{w}) > 0\ dB, \forall m. \end{array} \quad (6)$$

The first constraint guarantees that the ports either transmit at full power ($\alpha = 1$) or they are switched off, second constraint ensures that beamsteering coefficients do not alter the transmission power and the third constraint introduces fairness to the problem by lower limiting the SINR of all users. The search space of the problem is $\{0,1\}^{LM} \times \mathbb{C}_{|\cdot|=1}^{LM}$, where $\mathbb{C}_{|\cdot|=1}$ is the space of complex scalar with unit modulus.

For the Continuous Power Management (CPM) scenario, the first constraint in the above problem is relaxed, i.e.,

$$\begin{array}{ll} \max\limits_{\alpha,\mathbf{w}} & \mu(\alpha, \mathbf{w}) \\ \text{s.t.} & \alpha_{lm} \in [0,1], \forall l, m, \\ & |w_{lm}| = 1, \forall l, m, \\ & SINR_m(\alpha, \mathbf{w}) > 0\ dB, \forall m. \end{array} \quad (7)$$

The search space of this problem is $[0,1]^{LM} \times \mathbb{C}_{|\cdot|=1}^{LM}$.

The problems above are non-convex and it gets more difficult to solve them as the number of cells increase. Here, we propose to use Particle Swarm Optimization (PSO) to solve both problems. Further discussion on using PSO to solve a similar problem can be found in [16].

III. PERFORMANCE EVALUATION

We analyze the performance of the proposed method for a network scenario with $M = 2$ cells, where a hexagonal cell contains $L = 7$ ports, e.g., Fig. 1. One of the ports is located at the center of the cell, and others are located uniformly at a distance of $2/3$ of the circumradius (r_c) from the center to increase the coverage of the cell. Ports can either be switched off, or they can transmit at a fixed power level of $P_{\max}$ for BPM, or they can transmit at an adjustable power level in the interval $[0, P_{\max}]$ for CPM.

A single RB is considered, and at most one UE can use this RB in a cell. A UE is positioned randomly in each cell with uniform distribution. For the port-to-UE link, a Rayleigh fading channel with log-normal shadowing and path loss components as in [18] are considered. The complex channel gains are $h_{lnm} = \sqrt{\rho(d_{lnm}) s_{lnm}} h'_{lnm}$, where $\rho(\cdot)$ is the path loss function given below, d_{lnm} is the distance between the l-th port of the n-th cell and the user in the m-th cell, s_{lnm} represents log-normal shadowing with 0 dB mean and 8 dB standard deviation, h'_{lnm} denotes the fading effect and has a complex Gaussian distribution with zero mean and unit variance. For the suburban scenario described in [18], the distance between base stations is 1299 m, and the noise level is -114 dBm. The path loss function considered here is

$$\rho(d_{lnm}) = 10^{-(1.866 + 4.032 \log_{10}(d_{lnm}))}, \quad (8)$$

where carrier frequency is taken as 2 GHz, port antennas are at a height of 15 m, and each UE is assumed to have 1.5 m elevation. All results are averaged over 500 realizations. We consider a single RB in an LTE-like scenario with a bandwidth of 180 kHz. The data rates given below are calculated over this bandwidth. For the sake of simplicity we do not consider any modulation or coding schemes over the RB, data rates are calculated by using Shannon's capacity expression.

For the BPM and CPM scenarios, problems (6) and (7) are optimized by using PSO. The PSO algorithm used here has a structure similar to that in [16]. In the optimization problems, binary PSO [19] is used for BPM whereas conventional PSO is used for CPM. Population size is 500 particles and the inertia coefficient is taken as a function of the iteration number, linearly decreasing from $c_w = 0.9$ to $c_w = 0.4$, local and global acceleration coefficients are chosen as $c_l = 2$ and $c_g = 0.9$, respectively. For the two-cell network, iterations continue until 30 consecutive sum-rate values are contained in a neighbourhood of ± 1 kbits/s. Computational complexity of the algorithm is 12 multiplications per particle in CPM whereas there are 13 multiplications and 1 exponentiation per particle in BPM for one iteration. For the case of two-cell network, it is found that the average number of iterations for BPM and CPM are 39 and 46, respectively. Since beamsteering and port power coefficients are jointly optimized in this work, exhaustive search has a prohibitive computational complexity.

The behaviours of energy efficiency, sum-rate and transmission power versus the trade-off control parameter (c_p) for a certain $P_{\max}$ value in the two-cell scenario are depicted in Fig.s 2-4, respectively.

Maximizing traditional EE metric in equation (4) focuses on minimizing the power consumption as much as possible. However, the trade-off between sum-rate maximization and transmission power minimization expands the operation range, thus, a slight increase in transmission power with respect to the conventional EE approach will decrease the energy efficiency in terms of bits/Joule, but enables us to get significant gain in

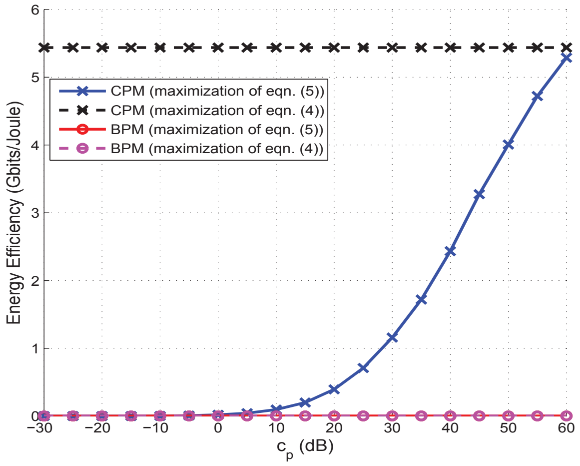

Fig. 2: Energy efficiency (sum-rate over total transmit power, i.e., $\frac{R}{P_T}$) achieved by maximizing the cost functions in (4) and (5) with different trade-off parameters by using Binary Power Management and Continuous Power Management versus trade-off parameter (c_p) in a two-cell network for $P_{\max} =$ 30 dBm.

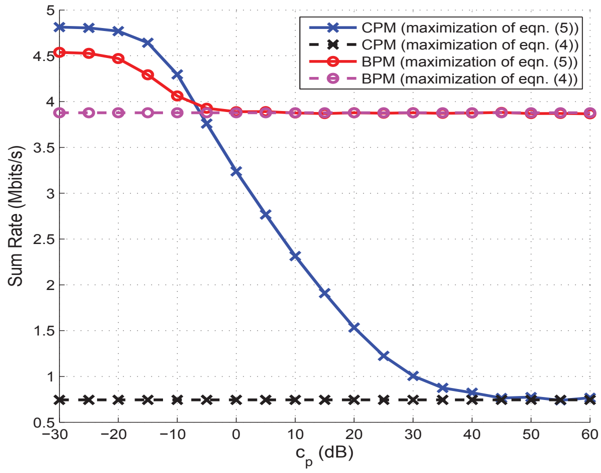

Fig. 3: Sum-rate achieved by maximizing the cost functions in (4) and (5) with different trade-off parameters by using Binary Power Management and Continuous Power Management versus trade-off parameter (c_p) in a two-cell network for $P_{\max} = 30$ dBm.

sum-rate. When maximization of sum-rate is relatively important, proposed cost function offers lower EE, however higher sum-rate values. As the minimization of the total transmission power becomes more dominant, proposed cost function with CPM method starts to follow EE curve of the classical one whereas BPM method offers almost same EE performance for the two cost functions. After a certain point, increasing c_p does not improve the performance and the cost functions converge in the limit. Moreover, CPM method performs better than BPM method since CPM method offers more freedom in the feasible set to maximize energy efficiency. The huge difference between CPM and BPM methods in energy efficiency depends on the transmission power performances.

Highest level for sum-rate is obtained when $c_p = 0$, i.e., sum-rate maximization is the only goal without energy efficiency concerns. When sum-rate maximization is relatively necessary (smaller c_p values), CPM method achieves higher rates; after the crossover point where $c_p \in [0.1, 1]$, power minimization takes priority, therefore sum-rate decreases due to low transmission power. In terms of energy efficiency, CPM performs better than BPM for both sides of the crossover point which can be verified from the Fig. 2. As c_p increases to higher values, sum rate decreases as expected but faces with a flooring effect. BPM method faces its lower limit early whereas sum-rate continues to decrease (with a decreasing slope) for CPM method. Effect of the proposed cost function can also be observed in Fig. 3, sum-rate will be underlimited with the traditional EE approach in (4) which will constitute a lower bound for the maximization of the proposed EE method in (5).

Fig. 4 demonstrates the sum of port power coefficients in a cell averaged over the network versus c_p. Multiplying this value by P_{max} gives the average total transmission power per cell. When energy efficiency concerns less (low c_p values), CPM method uses more transmission power than BPM, which results in higher sum-rate. However, in a two-cell scenario, as c_p increases after the crossover point, BPM method optimizes the network such that one port is transmitting at full power in each cell and others are switched-off whereas CPM appears to approach lower power levels with respect to BPM, while making it advantageous in terms of energy efficiency. Convergence of two energy efficiency cost functions can also be observed in Fig. 4 in terms of transmission power levels such that at low c_p values, the proposed EE approach uses more transmission power and gets close to its lower bound (traditional EE approach) as $c_p$increases.

Instead of as possibly as minimizing transmission power, slightly increasing transmission power may result in significant increase in sum-rate, especially for CPM method. Proposed energy efficiency cost function seems to be sensitive to the value of the trade-off parameter and offers to control the all operation states between sum-rate maximization and power minimization.

IV. Conclusion

In this paper, a coordinated multi-cell distributed antenna system is considered. In order to increase the coverage and throughput of the network, instead of employing a single base station in a cell, a number of ports are distributed throughout the cell which are transmitting the same signal (causing interference to neighbouring cells) and energy efficient resource allocation is carried out among the ports. Two transmission schemes are investigated; either the ports

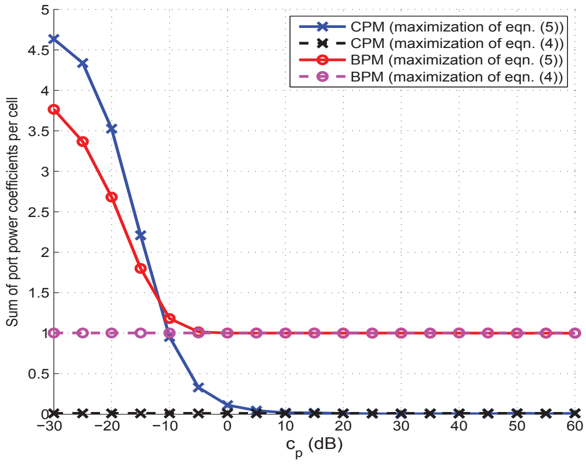

Fig. 4: Sum of port power coefficients per cell achieved by maximizing energy efficiency cost functions in (4) and (5) by using Binary Power Management and Continuous Power Management versus trade-off parameter (c_p) in a two-cell network for $P_{\max} = 30$ dBm.

are switched on and off (Binary Power Management, BPM) with a maximum transmission power limit per port or they are allowed to transmit with adjustable gains (Continuous Power Management, CPM). Beam steering coefficients are included to the optimization problem which increase not only the search space, thus, complexity, but also sum rate.

Since conventional energy efficiency concept has the potential to overlimit the sum-rate, a novel energy efficiency expression is introduced. It has been shown that by increasing transmission power slightly, significant increase in sum-rate can be obtained by exploiting the use of a trade-off between sum-rate maximization and transmission power minimization. Traditional energy efficiency cost function constitutes a lower bound to the proposed cost function in terms of sum rate and total tranmit power. Proposed energy efficiency expression offers more freedom to choose the operating data rate and converges to traditional one as minimizing transmission power becomes important.

It has been demonstrated that CPM outperforms BPM in terms of the energy efficiency for all operation states of trade-off. Proper power management introduces an important gain to system performance and power efficiency, which can be considered very promising for next generation networks.

Acknowledgment

This work is supported by TUBITAK (The Scientific and Technological Research Council of Turkey), Turkey, under project no. 112E024.

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