# Trade-Off between Spectral Efficiency and Energy Efficiency in Multi-Cell Uplink Networks

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*Abstract*— **In this paper, we investigate the effect of user scheduling and transmit power control on trade-off between spectral efficiency and energy efficiency in multi-cell uplink networks. We assume that each user adaptively controls the transmit power according to its generating interference to other cell base stations (BSs) and each BS schedules the user having the largest effective channel gain among users in a cell. The users transmit data with the peak power, $P_{MAX}$, if the generating interference to other cell BSs is smaller than a particular threshold, $\eta_I$. With the joint interference-aware power control (IAPC) and user scheduling, the trade-off between spectral efficiency and energy efficiency becomes significantly improved as the number of users in each cell increased, compared with the conventional maximum signal-to-noise ratio (maxSNR) user scheduling and minimum interference-to-noise ratio (minINR) user scheduling. In addition, the power consumption becomes significantly reduced with the IAPC and user scheduling for a given spectral efficiency.**

***Keywords*— Spectral efficiency, energy efficiency, trade-off, multi-user diversity, interference-aware power control**

## I. INTRODUCTION

Spectral efficiency (SE) in cellular networks has been considered as one of the most important performance metrics and many techniques have been proposed for improving the SE. Among them, interference management is one of the most challenging issues to improve the SE especially in multi-cell networks [1] because the cellular network is recently becoming crowded with wireless user devices and small base stations (BSs). On the other hand, the amount of energy consumed in cellular networks becomes dramatically increased. Therefore, it is important to improve the SE of the cellular network with the low energy consumption [2]. It was shown that there exists a fundamental trade-off between SE and EE, and this relationship between SE and EE needs to be carefully considered in designing the wireless networks [3]. An evaluation framework for various communication techniques in terms of energy efficiency has been proposed for 5G systems [4]. In particular, the EE of emerging techniques including massive multiple-input multiple-output (MIMO), device-to-device (D2D) communications, and ultra-dense networks (UDNs) be investigated for 5G systems.

Interference management plays an important role in improve the EE in interference-limited wireless networks [5-7]. In [5], the trade-off between SE and EE has been investigated in multi-user interference-limited networks (i.e., interference channel in information theory) under *perfect* channel state information (CSI) at all communicating nodes, which is not feasible in

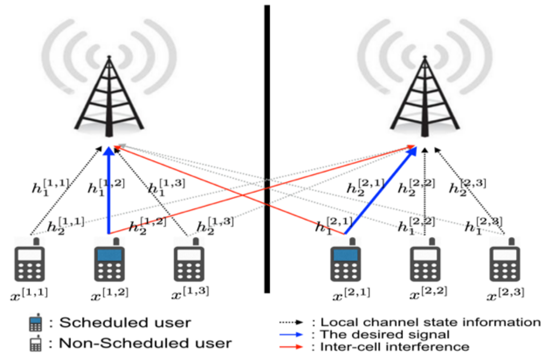


Figure 1. System model with K=2, N=3

practical cellular networks. In [6], the optimization algorithm based on iterative power allocation was proposed for improving the SE-EE trade-off in multi-user interference-limited wireless networks, assuming perfect CSI as well. In [7], the SE-EE trade-off was investigated in cellular downlink networks, where multi-cell downlink networks are also considered via stochastic geometry framework. Even though there exist several studies on SE-EE trade-off in interference-limited wireless networks, the SE-EE trade-off in *multi-cell uplink networks* has not been investigated to the best of our knowledge. In addition, the existing studies did not consider user scheduling though it is one of the most important techniques in practical cellular networks.

In this paper, we investigate the effect of the user scheduling and transmit power control on the SE-EE trade-off in TDD multi-cell uplink networks. In addition, we assume that each user only knows the wireless channel from itself to BSs (i.e., local CSI), which is a practical assumption. Each cell is assumed to operate with a distributed manner, which implies each BS selects the user independently without coordination among BSs.

## II. SYSTEM MODEL

We consider the time division duplex (TDD) interfering multiple-access channel (IMAC) model which has been widely used for describing practical cellular networks in the literature. We assume that there exist K cells and each cell consists of a single BS and N users. In addition, both the BS and the user are equipped with a single antenna. For example, Fig. 1 illustrates the case when K = 2 and N = 3. We assume a block fading channel where the wireless channel matrices remain constant

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during a transmission block (e.g., frame) and independently change for every transmission block. We assume that each BS selects a single user for data transmission at each transmission block. Without loss of generality, we assume that the index of the scheduled user is denoted by $s$ in each cell for notional simplicity. Let $P^{[i,j]}(\leq P_{\text{MAX}})$ and $x^{[i,j]}$ be the transmit power and the symbol of the $j$-th user in $i$-th cell ($j \in \mathcal{N} = \{1, 2, \ldots, N\}$ and $i, k \in \mathcal{K} = \{1, 2, \ldots, K\}$), respectively.
Then, the received signal at the $k$-th base station, $y_k \in \mathbb{C}$, is given by

$$y_k = \underbrace{\sqrt{P^{[k,s]}} h_k^{[k,s]} x^{[k,s]}}_{\text{desired signal}} + \underbrace{\sum_{j=1, j\neq k}^{K} \sqrt{P^{[j,s]}} h_k^{[j,s]} x^{[j,s]}}_{\text{inter-cell interference}} + z_k \quad (1)$$

As noted before, $s$ denotes the index of the scheduled user in a cell for uplink data transmission. $h_k^{[i,j]} \in \mathbb{C}$ denotes the wireless channel coefficient form the $j$-th user in the $i$-th cell to $k$-th BS, which is assumed to follow a complex Gaussian distribution with zero mean and unit variance, i.e., $h_k^{[i,j]} \sim \mathcal{CN}(0,1)$, and to be independent across different $i$, $j$ and $k$. Assuming channel reciprocity of the TDD system, it is assumed that each user perfectly estimates the uplink channels from itself to all base stations, $h_k^{[i,j]}$, for all $k$ via the pilot signals from all BSs. Hence, local channel state information (CSI) is assumed in this paper. $z_k \in \mathbb{C}$ denotes the circular symmetric complex additive white Gaussian noise with zero mean and variance $N_0$, i.e., $z_k \sim \mathcal{CN}(0, N_0)$. Note that we do not assume any coordination or exchange of information among BSs.

## III. Interference-aware power control

In this section, we describe the overall procedure of the interference-aware power control.

### A. Overall Procedure

**1) *Reference signals & interference threshold broadcast*:** Each BS sends the pre-determined reference signal to enable users to obtain its local CSI to all BSs. Then, each user estimates the wireless channel coefficient from itself to all BSs. Each BS also sends a pre-determined positive threshold of generating other-cell interference, $\eta_I$, to all users in the network as a system parameter. The threshold indicates the maximum value of the allowable generating interference from each user to other cell BSs, which is normalized by $P_{\text{MAX}}$.

**2) *Interference-aware power control and scheduling metric feedback:*** The sum of generating interferences from the $j$-th user in the $i$-th cell to $k$-th BS is given by

$$\eta_k^{[i,j]} = \|h_k^{[i,j]}\|^2 \quad (2)$$

where $i \in \mathcal{K}, j \in \mathcal{N},$ and $k \in \mathcal{K} \backslash i = \{1, 2, \cdots, i-1, i+1, \cdots, K\}$. Then, the sum of the generating interferences of the $j$–th user in the $i$–th cell can be expressed as

$$\eta^{[i,j]} = \sum_{k=1, k\neq i}^{K} \eta_k^{[i,j]} \quad (3)$$

In the proposed technique, the transmit power of the $j$–th user in the $i$–th cell is determined as

$$P^{[i,j]} = \begin{cases} P_{\text{MAX}} & \text{if } \eta^{[i,j]} \leq \eta_I \\ \frac{\eta_I}{\eta^{[i,j]}} P_{\text{MAX}} & \text{otherwise,} \end{cases} \quad (4)$$

where $\eta_I$ denotes the normalized maximum interference. Each user adjusts the transmit power-level according to its generating interference to other cells. The transmit power of the proposed scheduling can be also expressed as

$$P^{[i,j]} = \min\{P_{\text{MAX}}, \frac{\eta_I}{\eta^{[i,j]}} \cdot P_{\text{MAX}}\}. \quad (5)$$

Based on the transmit power, the corresponding desired channel gain of the $j$-th user in the $i$-th cell is given by

$$\rho^{[i,j]} \triangleq P^{[i,j]} \cdot \|h_i^{[i,j]}\|^2 \quad (6)$$

which is fed back from each user to its serving BS as a scheduling metric.

**3) *User scheduling:*** Upon receiving N users' scheduling metrics at the serving cell, the BS selects user with the largest effective channel gain. As noted before, we assume that s denotes the index of the scheduled user and the scheduling index, $s$ in the $k$-th cell is computed by

$$s_k^{\text{IA-PC}} = \arg\max_j \rho^{[k,j]}. \quad (7)$$

### B. Performance metric: SE and EE

We consider both spectral efficiency and energy efficiency as performance metrics of the interference-aware power control technique combined with user scheduling. First, signal-to-interference plus noise ratio (SINR) at the k-th BS, $y_k \in \mathbb{C}$, is given by

$$\text{SINR}_k = \frac{|h_k^{[k,s]}|^2 \cdot P^{[k,s]}}{I_k + N_0}, \quad (8)$$

where the inter-cell interference, $I_k$, is given by

$$I_k = \sum_{i=1, i\neq k}^{K} \alpha |h_k^{[i,j]}|^2 \cdot P^{[i,s]}. \quad (9)$$

The term $\alpha$ $(0 < \alpha < 1)$ denotes the attenuation parameter which captures the effect of distance from the users in other cells. Then, with Shannon capacity formular, the spectral efficiency of the k-th cell is given by

$$\text{SE}_k = \log_2(1 + \frac{|h_k^{[k,s]}|^2 \cdot P^{[k,s]}}{I_k + N_0}) \quad (10)$$

and the energy efficiency of $k$-th cell is also given by

$$\text{EE}_k = \frac{\text{SE}_k}{P^{[k,s]} + P_c} \quad (11)$$

where $P_c$ denotes the circuit power at the $k$-th BS. We assume that the maximum transmit power at users and the circuit power at BSs are equal each other. The spectral efficiency and energy efficiency trade-off is hard to analyse due to the non-convexity of the SINR. Therefore, in this paper, we evaluate the trade-off relationship with computer simulations.

## IV. Simulation results

In this section, we validate the proposed IAPC with user scheduling via extensive computer simulations. We also consider the conventional user scheduling algorithms as references: maximum signal-to-noise ration (*maxSNR*) and minimum interference-to-noise ratio (*minINR*) algorithms. The maxSNR scheduling algorithm selects the user having the maximum SNR without considering inter-cell interference, which is known to yield the optimal performance in a single cell network. The scheduling algorithm of the maxSNR in the $k$–th cell is given by

$$s_k^{\mathrm{MaxSNR}} = \arg\max_j |h_k^{[k,j]}|^2, \quad j = 1,2,\cdots N \quad . \tag{12}$$

The minINR scheduling algorithm has been known to yield a better performance than the maxSNR scheduling algorithm in an interference-limited cellular network. The scheduling algorithm of the minINR in the $k$–th cell is given by

$$s_k^{\mathrm{minINR}} = \arg\min_j \left[ \sum_{i=1, i\neq k}^{K} |h_k^{[i,j]}|^2 \right], \; j = 1,2,\cdots N \quad . \tag{13}$$

Fig. 2 illustrates the SE and EE trade-off when K = 3, $\alpha$ = 0.5, $P_c$ = 20 dBm, and N = 30, 50, 100, respectively. We observe that the IAPC scheduling algorithm yields a significantly improved trade-off relationship compared with the conventional algorithms. In this simulation, we assume that the optimum threshold is used for the IAPC scheduling algorithm. For given parameters, the optimal threshold is numerically determined. The trade-off becomes improved as the number of users in a cell increases for all scheduling algorithm. Fig. 3 shows the power consumption of the scheduling algorithms for achieving the spectral efficiency when K = 3, $\alpha$ = 0.5, $P_c$ = 20 dBm, and N = 30, 50, 100, respectively. For each scheduling algorithm, there exists a limit of the spectral efficiency which cannot be achieved. The IAPC algorithm significantly reduces the power consumption for a given spectral efficiency. In addition, the power consumption becomes decreased as the number of users in a cell increases due to the multiuser diversity.

## V. Conclusion

We investigate the effect of the user scheduling and the transmit power control on the trade-off between spectral efficiency (SE) and energy efficiency (EE) in multi-cell multi-user uplink networks. Simulation results show that the user scheduling algorithm with IAPC significantly outperforms the conventional scheduling algorithms in terms of the trade-off SE and EE and the power consumption.


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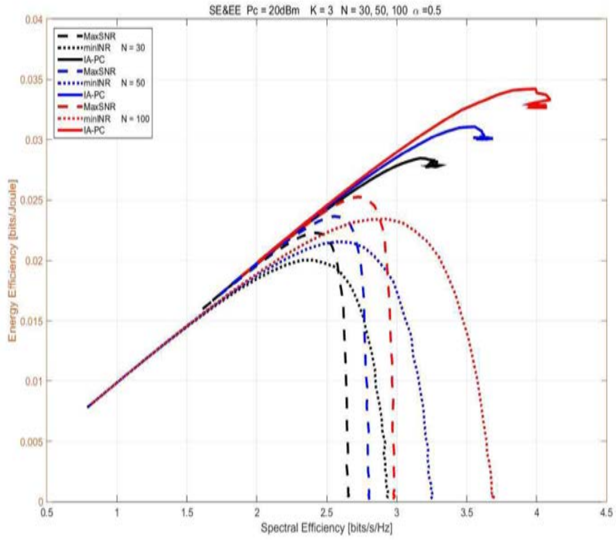


Fig. 2. Trade-off between SE and EE for varying the number of users in a cell when $P_c$=20dBm, K = 3, and $\alpha$ =0.5.

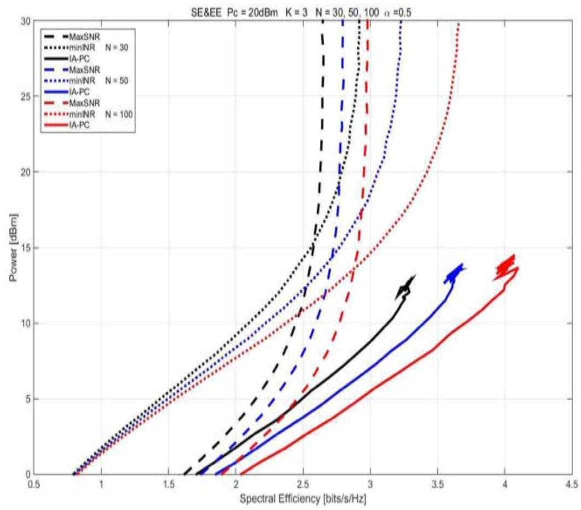


Fig. 3. Power consumption for varying the spectral efficiency with different the number of users in a cell when $P_c$=20dBm, K = 3, and $\alpha$ =0.5.

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