On the CDF-Based Scheduling for Multi-Cell Uplink Networks

Hu Jin, Bang Chul Jung†, and Victor C. M. Leung*
Dept. ECE, Hanyang University, Ansan, 426-791, Republic of Korea
†Dept. ICE, Gyeongsang National University, Tongyeong, 650-160, Republic of Korea
*Dept. ECE, The University of British Columbia, Vancouver, Canada V6T 1Z4
E-mail: hjin@ece.ubc.ca; bcjung@gnu.ac.kr; vleung@ece.ubc.ca

***Abstract*—In this paper, we propose a cumulative distribution function (CDF)-based scheduling for *multi-cell* uplink networks in order to exploit multi-user diversity, while satisfying fair resource sharing among users. In the proposed scheduling, each user adjusts its transmit power to reduce the amount of generating interference to other cells, based on a pre-determined threshold. Then, each user calculates CDF of an uplink signal-to-noise ratio with the adjusted transmit power, and feeds the CDF value back to its serving base station (BS). In each time slot, the BS selects the user having the largest CDF value. The proposed scheduling operates with a *distributed* manner even though it effectively copes with inter-cell interference. As a main result, we prove that the proposed scheduling achieves the double-logarithmic growth of normalized user throughput which is defined as the ratio of user throughput to the probability of the user being selected. Moreover, we observe that a fixed threshold is enough to accommodate diverse network scenarios with different population sizes and user locations in the proposed scheduling.**

***Index Terms*—Inter-cell interference, cellular uplink, fairness, user scheduling, CDF-based scheduling.**

I. Introduction

In wireless communications, independent fading of users provides multi-user diversity. Extensive studies on user scheduling have been performed to exploit the multi-user diversity in cellular systems. For single-cell systems, the optimal user scheduling in terms of throughput is to select the user having the largest channel gain at each time slot both in uplink [1] and downlink [2]. However, the above scheduling may cause a fairness problem among users in a cell since a base station (BS) may select the users closer to itself more frequently due to their higher average signal-to-noise ratios (SNRs).

The fairness problem in the single-cell systems has been widely studied with various criteria, such as throughput-based fairness [3], [4] and resource-based fairness [5]–[9]. In this paper, we focus on the resource-based fairness which requires fair resource sharing among users. For example, a round-robin scheduling equally assigns the time resource to users in turn and thus, strictly meets the fair resource sharing requirement. However, it fails to exploit the multi-user diversity. A user scheduling based on the normalized-SNR [5] also equally assigns the time resource to users when the users experience the fading which is distributed with the same shape. It, however, cannot guarantee the fair resource sharing when the users experience the fading with different distributions. Liu *et al.* proposed an opportunistic user scheduling to maximize the sum throughput while satisfying resource sharing requirements [6]. It should calculate the 'offset' value iteratively in order to guarantee the fairness, which limits its applications to various communication scenarios.

Later, several scheduling algorithms [7]–[9] were proposed to assign the time resource to users by comparing users' cumulative distribution function (CDF) values of channel gains. For convenience, we call those algorithms *CDF-based scheduling (CS)* in this paper. In the CS, the user having relatively better channel gain is selected. As the CDF value is uniformly distributed between $[0,1]$, all users are equally selected in the CS. Due to its simplicity, the CS has been investigated under various network scenarios [10]–[12]. To the best our knowledge, however, the CS has not been considered for multi-cell uplink networks.

Despite extensive studies on user scheduling for exploiting multi-user diversity in cellular systems, the uplink multi-cell scenario was considered rather limited because of the difficulty in handling an unexpected inter-cell interference [13], [14]. In the uplink multi-cell networks, each BS cannot predict the amount of the received inter-cell interference from other cells since the BS has no information of the selected users in other cells. Hence, handling the inter-cell interference is one of the most challenging problems in designing uplink user scheduling for multi-cell networks. Recently, an opportunistic user scheduling was proposed to exploit the multi-user diversity in uplink multi-cell networks, but the user fairness was not considered [15].

In this paper, we propose an efficient user scheduling algorithm not only exploiting the multi-user diversity but also satisfying the resource-based fairness among users for uplink multi-cell networks. We introduce a threshold of generating interference to other cells as in [15], which scales down the transmit power of users. Then, each user calculates the CDF of the uplink signal-to-noise ratio with the adjusted transmit power and feeds the CDF value back to the serving BS. In each time slot, the BS selects the user with the largest CDF value. Therefore the proposed scheduling basically operates in the same way as the convetional CS except for the power adjustment of users according to the generating interference to

978-1-4799-2003-7/14/$31.00 ©2014 IEEE

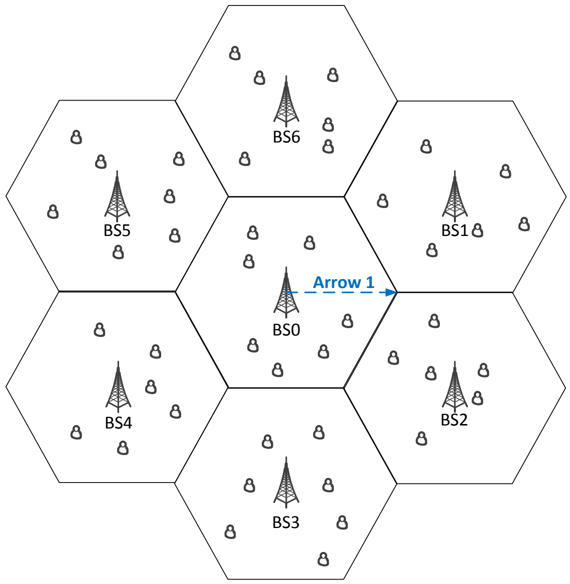

Fig. 1. System model ($M = 6$).

other cells. We call the proposed scheduling CS with inter-cell interference (CS-ICI). It should be noted that the scheduling for downlink multi-cell networks can be easily extended from the conventional CS algorithms which are designed for the single-cell network since the interference from other cells is predictable due to fixed location of BSs.

As a performance measure for the efficiency of certain user scheduling algorithms, a throughput scaling has been studied extensively in the literature [16], [17]. The throughput scaling illustrates how fast the throughput improves as the number of users in a network increases. For a single-cell network, it has been shown in [16] that the sum throughput increases in a scale of $\ln \ln N$ as the number of users N tends to infinity. For uplink multi-cell networks, Shin *et al.* proved that the throughput scaling of $\ln \ln N$ is also possible even when inter-cell interference exists [15]. When the CS is considered for the fair resource sharing among users, it was shown that the CS achieves the $\ln \ln N$ scaling in terms of the normalized throughput which is defined as the ratio of user throughput to its assigned time fraction [17]. In this paper, we prove that the proposed CS-ICI achieves the normalized throughput scaling of $\ln \ln N$, satisfying the resource-based user fairness, even in the presence of inter-cell interference.

The rest of this paper is organized as follows: Section II introduces the system model. Section III presents the proposed CS-ICI scheduling. Section IV analyzes the normalized throughput scaling of the CS-ICI. Section V shows the performance. Finally, conclusion is drawn in Section VI.

II. System Model

We observe a cell which is surrounded by M interfering cells. One-tier interference model is considered as it is the main and dominant source of interference in multi-cell networks. Each cell has a BS and N users each of which is equipped with a single antenna. At each time slot, each BS selects one user to transmit packet to the BS. We denote the cell being observed by cell 0 and the interfering cells by cell 1, $2, \cdots, M$. Fig. 1 shows an example of hexagonal-cell structure where cell 0 is surrounded by cell $1, 2, \cdots, 6$.

Let $\alpha_{iu_m} h_{iu_m}$ denote the channel gain between user u_m in cell m and BS i for $u_m \in \{1, 2, \cdots, N\}$, and $i, m \in \{0, 1, \cdots, M\}$ where α_{iu_m} is the large-scale path-loss component and h_{iu_m} is the small-scale fading component. The small scale fading channel is complex Gaussian having zero mean and unit variance, i.e., the channel is Rayleigh fading. The small scale fading is independent across different transmit-receive pairs. Due to the spatially distributed user locations, users may experience different large-scale path-loss. We also assume a block-fading model where the channel gain is fixed during one slot and is changed independently between different slots.

When users $u_0, u_1, \cdots, u_M$ are selected to transmit in a time slot, the received signal at BS 0 is given as

$$y_0 = \alpha_{0u_0} h_{0u_0} x_{u_0} + \sum_{m=1}^{M} \alpha_{0u_m} h_{0u_m} x_{u_m} + z_0, \qquad (1)$$

where $y_0 \in \mathbb{C}$ is the received signal, $x_{u_m} \in \mathbb{C}$ is the transmitted signal of user u_m in cell m, and $z_0 \in \mathbb{C}$ is a zero-mean circular-symmetric Gaussian random vector, $z_0 \sim CN(0, N_0)$. The transmit power constraint is set to P, i.e., $E[|x_{u_m}|^2] \leq P$. If all the users $u_0, u_1, \cdots, u_M$ transmit with power P, the SINR of x_{u_0} at BS 0 is

$$\begin{aligned} \eta_{0u_0} &= \frac{P|\alpha_{0u_0} h_{0u_0}|^2}{N_0 + P \sum\limits_{m=1}^{M} |\alpha_{0u_m} h_{0u_m}|^2} \\ &= \frac{\gamma_{0u_0}}{1 + \sum\limits_{m=1}^{M} \gamma_{0u_m}}, \end{aligned} \qquad (2)$$

where $\gamma_{iu_m} = P|\alpha_{iu_m} h_{iu_m}|^2 / N_0$ is the SNR for user u_m's signal received at BS i when the users in other cells are assumed to keep silence. Since the channel is complex Gaussian, γ_{iu_m} is exponentially distributed with mean $\overline{\gamma}_{iu_m} = P|\alpha_{iu_m}|^2 / N_0$. Let $F_{\gamma_{iu_m}}(\gamma)$ denote the CDF of γ_{iu_m}. Then, it is expressed as

$$F_{\gamma_{iu_m}}(\gamma) = 1 - e^{-\frac{\gamma}{\overline{\gamma}_{iu_m}}}. \qquad (3)$$

For the channel estimation, the BSs transmit training (or pilot) signals in turn or in orthogonal dimensions so that each user can estimate the channel gains from the serving and interfering BSs. In the case of time division duplex (TDD), the estimated channel gains at each user are the same as those from the user to the corresponding BSs. Therefore, users are able to estimate the SNRs, $\gamma_{iu_m} (i \in \{0, 1, \cdots, M\})$, received at the corresponding BSs and obtain the CDF of $F_{\gamma_{iu_m}}(\gamma)$ over long-term observations when the channels are stationary.

As we can see from (2), one challenge in designing uplink scheduling for multi-cell networks is to overcome the inter-cell interference. Note that each BS is only able to select users in its cell and cannot control the transmissions of the users in other cells. Therefore, each BS or user cannot predict the SINR before the user selections are performed by all BSs while the SINR mainly affects the transmission data rate and the successfulness of the packet transmissions.

III. CDF-based Scheduling in the Presence of Inter-Cell Interference

We first introduce a scheme that simply extends the conventional CS in Section III-A in order to be applicable for uplink multi-cell networks. Then, we introduce the CDF-based scheduling with inter-cell interference (CS-ICI) in Section III-B. As a representative example, we describe the user scheduling procedure performed in cell 0.

A. CS with Simple Extension (CS-SE)

In each slot, the user selection procedure of the CS with simple extension (CS-SE) in cell 0 is as follows:

1) User u_0 feeds the value of $U_{0u_0} = F_{\gamma_{0u_0}}(\gamma)$ back to BS 0 where γ is the current SNR. After receiving the feedback information from all users, BS 0 selects a user who shows the largest feedback value.
2) The selected user transmits its packet with a data rate of $\theta \log_2(1+\gamma)$ where $\theta \in (0,1)$.

Note that each user cannot use the CDF of SINR η_{0u_0} because it has no information of the inter-cell interference in the uplink. Moreover, if the user being selected chooses the data rate of $\log_2(1+\gamma)$, outage would be happen frequently due to the inter-cell interference. Hence the user should reduce the data rate by a factor of θ in order to prevent the frequent outage events. Suitable values of θ will be shown in Section V.

It is easy to prove that the feedback information $U_{0u_0} = F_{\gamma_{0u_0}}(\gamma)$ is uniformly distributed between $[0,1]$ and the CDF is given by

$$F_{U_{0u_0}}(u) = u, \qquad u \in [0,1]. \tag{4}$$

Therefore, the probability that each user is selected by its serving BS is $1/N$ due to the symmetric property of the feedback values, i.e., CS-SE satisfies the fair resource sharing requirement.

B. CS with Inter-Cell Interference (CS-ICI)

The main idea of the proposed CS with inter-cell interference (CS-ICI) is to control the generating interference of each user to other cells to be lower than a certain threshold. Specifically, a threshold $\gamma_{\rm th}$ is applied to scale down the transmit power of each user when its SNR received at any neighbor BS is larger than $\gamma_{\rm th}$.

Let $\gamma_{\max,u_0} = \max(\gamma_{1u_0}, \gamma_{2u_0}, \cdots, \gamma_{Mu_0})$ denote the maximum SNR received by the neighbor BSs when user u_0 transmits with the power of P. Then, the CDF of $\gamma_{\max,u_0}$ is expressed as

$$F_{\gamma_{\max,u_0}}(\gamma) = \prod_{k=1}^{M} F_{\gamma_{ku_0}}(\gamma), \tag{5}$$

where $F_{\gamma_{ku_0}}(\gamma)$ is shown in (3).

After the threshold-based power control of CS-ICI, user u_0's SNR received by the serving BS 0 is

$$\rho_{0u_0} = \begin{cases} \gamma_{0u_0}, & \text{if } \gamma_{\max,u_0} \le \gamma_{\rm th}, \\ \gamma_{0u_0}\dfrac{\gamma_{\rm th}}{\gamma_{\max,u_0}}, & \text{if } \gamma_{\max,u_0} > \gamma_{\rm th}. \end{cases} \tag{6}$$

Hence, user u_0's SNRs at the neighbor BSs are all smaller than $\gamma_{\rm th}$. Based on the CDFs of γ_{0u_0} and $\gamma_{\max,u_0}$ shown in (3) and (5), the CDF of ρ_{0u_0} is calculated as

$$\begin{aligned} F_{\rho_{0u_0}}(\rho) &= \Pr\{\gamma_{0u_0} \le \rho, \gamma_{\max,u_0} \le \gamma_{\rm th}\} \\ &\quad + \Pr\left\{\gamma_{0u_0}\frac{\gamma_{\rm th}}{\gamma_{\max,u_0}} \le \rho, \gamma_{\max,u_0} > \gamma_{\rm th}\right\} \\ &= F_{\gamma_{0u_0}}(\rho) F_{\gamma_{\max,u_0}}(\gamma_{\rm th}) \\ &\quad + \int_{\gamma_{\rm th}}^{\infty} F_{\gamma_{0u_0}}\left(\frac{x}{\gamma_{\rm th}}\rho\right) dF_{\gamma_{\max,u_0}}(x). \end{aligned} \tag{7}$$

As user u_0 controls its transmit power only based on its local information, it can obtain the CDF of $F_{\rho_{0u_0}}(\rho)$ through long-term observations on the channels. Based on this function, the user selection procedure of CS-ICI is given as follows:

1) In each time slot, user u_0 feeds the value of $V_{0u_0} = F_{\rho_{0u_0}}(\rho)$ back to BS 0, where ρ is the estimated SNR at the serving BS 0 when the threshold-based power control is applied. BS 0 selects a user who shows the largest feedback value.
2) If selected, user u_0 sets the data rate of $\log_2\left(1+\frac{\rho_{0u_0}}{1+M\gamma_{\rm th}}\right)$ and transmits a packet.

The data rate of $\log_2\left(1+\frac{\rho_{0u_0}}{1+M\gamma_{\rm th}}\right)$ is achievable because the users in neighbor cells also perform power control with CS-ICI. As the feedback information $V_{0u_0} = F_{\rho_{0u_0}}(\rho)$ is still uniformly distributed between $[0,1]$, the probability of user u_0 being selected is $1/N$.

In the remaining of this subsection, we analyze the lower-bound of the achievable throughput for u_0 in cell 0. As derived in [12], the received SNR at the BS when user u_0 is selected is given as

$$F_{{\rm sel},u_0}(\rho) = \left[F_{\rho_{0u_0}}(\rho)\right]^N. \tag{8}$$

Moreover, as the CS-ICI bounds the amount of inter-cell interference by $M\gamma_{\rm th}$, the SINR at BS 0 when user u_0 is transmitting is lower-bounded by

$$\eta_{0u_0} \;\ge\; \frac{\rho_{0u_0}}{1+M\gamma_{\rm th}}. \tag{9}$$

From (8) and (9), the throughput lower-bound for user u_0 with CS-ICI can be readily calculated as

$$\begin{aligned} S_{\rm CS-ICI} &= \frac{1}{N}\int_0^{\infty} \log_2(1+x) dF_{\eta_{0u_0}}(x) \\ &\ge \frac{1}{N}\int_0^{\infty} \log_2\left(1+\frac{\rho}{1+M\gamma_{\rm th}}\right) d\left[F_{\rho_{0u_0}}(\rho)\right]^N, \end{aligned} \tag{10}$$

where the factor of $1/N$ is the probability of user u_0 being selected. From (10) we can see that the throughput lower-bound is independent form the time-varying inter-cell interference caused by different users selected in other cells. As the throughput is a function of γ_{th}, a proper threshold value should be selected. We shall specify the suitable values of γ_{th} in Section V. Although $S_{\text{CS-ICI}}$ is not analyzed in a closed form, it will be used in deriving the throughput scaling law in Section IV.

IV. Throughput Analysis

Conventionally, the efficiency of a certain user scheduling is examined by observing its achievable throughput scaling when increasing the number of users to infinity. For the systems maximizing the sum throughput, it has been proven respectively in [15] and [16] that the throughput scaling of $\ln\ln N$ is achievable in both uplink and downlink cellular networks. When the resource-based fairness is considered, the $\ln\ln N$ growth of the normalized throughput was also observed in [17] for single-cell networks. In this section, we prove that the proposed CS-ICI is also capable of supporting $\log\log N$ growth of the normalized throughput in uplink multi-cell networks when the number of users increases to infinity.

In this section, we still observe the throughput of user u_0 in cell 0. From (7), we have

$$F_{\rho_{0u_0}}(\rho) \le F_{\gamma_{0u_0}}(\rho) F_{\gamma_{\max,u_0}}(\gamma_{\text{th}}) + 1 - F_{\gamma_{\max,u_0}}(\gamma_{\text{th}}) \quad (11)$$

where the inequality comes from the fact that $F_{\gamma_{0u_0}}\left(\frac{x}{\gamma_{\text{th}}}\rho\right) \le 1$. Let us define ρ_0 and $\beta \in (0,1)$ that satisfy

$$F_{\rho_{0u_0}}(\rho_0) = 1-\beta, \quad \Rightarrow \quad \rho_0 = F^{-1}_{\rho_{0u_0}}(1-\beta). \quad (12)$$

Substituting ρ_0 and β to (11), we have

$$\begin{aligned} &F_{\gamma_{0u_0}}(\rho_0) \ge 1 - \frac{\beta}{F_{\gamma_{\max,u_0}}(\gamma_{\text{th}})}, \\ &\quad \Rightarrow \quad \rho_0 \ge F^{-1}_{\gamma_{0u_0}}\left(1 - \frac{\beta}{F_{\gamma_{\max,u_0}}(\gamma_{\text{th}})}\right), \end{aligned} \quad (13)$$

where the increasing property of CDF is applied. Comparing (12) with (13), we have

$$F^{-1}_{\rho_{0u_0}}(1-\beta) \ge F^{-1}_{\gamma_{0u_0}}\left(1 - \frac{\beta}{F_{\gamma_{\max,u_0}}(\gamma_{\text{th}})}\right). \quad (14)$$

As the normalized throughput is defined as the ratio of user throughput to the probability of the user being selected, the normalized throughput of user u_0 with CS-ICI is calculated as

$$\begin{aligned} S^{\text{norm}}_{\text{CS-ICI}} &= N \cdot S_{\text{CS-ICI}} \\ &\ge \int_0^\infty \log_2\left(1 + \frac{\rho}{1+M\gamma_{\text{th}}}\right) d\left(F_{\rho_{0u_0}}(\rho)\right)^N \\ &\ge \int_z^\infty \log_2\left(1 + \frac{\rho}{1+M\gamma_{\text{th}}}\right) d\left(F_{\rho_{0u_0}}(\rho)\right)^N \\ &\ge \log_2\left(1 + \frac{z}{1+M\gamma_{\text{th}}}\right) \int_z^\infty d\left(F_{\rho_{0u_0}}(\rho)\right)^N \\ &= \log_2\left(1 + \frac{z}{1+M\gamma_{\text{th}}}\right) \left[1 - \left(F_{\rho_{0u_0}}(z)\right)^N\right]. \end{aligned} \quad (15)$$

TABLE I
System Parameters

Parameter	Values
Cell structure	Hexagon
Cell radius	500 m
User distribution	Uniform
Frequency	2 GHz
Bandwidth	10 MHz
Transmit power of each user	23 dBm
N_0	-199 dBW/Hz
Path-loss at 1 m	15.3
Path-loss exponent	3.76

If we set $z = F^{-1}_{\rho_{0u_0}}\left(1 + \frac{1}{N}\ln\frac{1}{N}\right)$, $S^{\text{norm}}_{\text{CS-ICI}}$ can be further derived as

$$\begin{aligned} &S^{\text{norm}}_{\text{CS-ICI}} \\ &= \log_2\left(1 + \frac{F^{-1}_{\rho_{0u_0}}\left(1+\frac{1}{N}\ln\frac{1}{N}\right)}{1+M\gamma_{\text{th}}}\right)\left[1 - \left(1 + \frac{1}{N}\ln\frac{1}{N}\right)^N\right] \\ &\ge \log_2\left(1 + \frac{F^{-1}_{\gamma_{0u_0}}\left(1 + \frac{\frac{1}{N}\ln\frac{1}{N}}{F_{\gamma_{\max,u_0}}(\gamma_{\text{th}})}\right)}{1+M\gamma_{\text{th}}}\right) \\ &\qquad \times \left[1 - \left(1 + \frac{1}{N}\ln\frac{1}{N}\right)^N\right], \end{aligned} \quad (16)$$

where the inequality is the result of applying (14) with $\beta = -\frac{1}{N}\ln\frac{1}{N}$. Based on the expression of $F_{\gamma_{0u_0}}(\gamma)$ in (3), for a value $\epsilon \in (0,1)$ we have [16]

$$F^{-1}_{\gamma_{0u_0}}(1-\epsilon) = \overline{\gamma}_{0u_0}\left[\ln\left(\frac{1}{\epsilon}\right) + O\left(\ln\ln\left(\frac{1}{\epsilon}\right)\right)\right], \quad (17)$$

where $\overline{\gamma}_{0u_0}$ is the average SNR. Moreover, as N increases to infinity we have

$$\lim_{N\to\infty}\left(1 + \frac{1}{N}\ln\frac{1}{N}\right)^N = 0. \quad (18)$$

Finally, applying (17) and (18), we can obtain the asymptotic performance of $S^{\text{norm}}_{\text{CS-ICI}}$ as

$$\begin{aligned} &\lim_{N\to\infty} S^{\text{norm}}_{\text{CS-ICI}} \\ &\ge \lim_{N\to\infty}\log_2\left(1 + \frac{\overline{\gamma}_{0u_0}\left[\ln\left(\frac{1}{-\frac{1}{N}\ln\frac{1}{N}}\right) + O(\ln\ln N)\right]}{1+M\gamma_{\text{th}}}\right) \\ &= \log_2 e \cdot \lim_{N\to\infty}\ln\left(1 + \frac{\overline{\gamma}_{0u_0}}{1+M\gamma_{\text{th}}}\ln N + O(\ln\ln N)\right). \\ &= \log_2 e \cdot \lim_{N\to\infty}\ln\ln N + O(\ln\ln\ln N). \end{aligned} \quad (19)$$

Hence, we can observe that $S^{\text{norm}}_{\text{CS-ICI}}$ increases in a scale of $\ln\ln N$ as N increases to infinity. Note that this scaling is always achievable as long as the threshold γ_{th} is fixed to any finite value.

V. Numberical Examples

In this section, we present simulation results to show the efficiency of the proposed CS-ICI in exploiting multi-user diversity. The considered networks scenario is shown in Fig. 1 and detailed simulation parameters are presented in Table I.

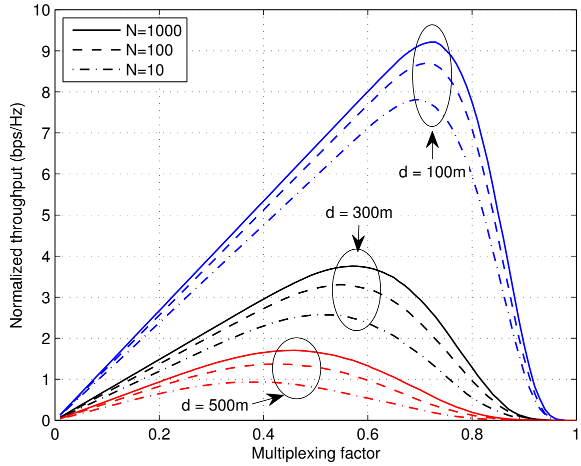

Fig. 2. Normalized throughput of CS-SE vs. multiplexing factor (θ).

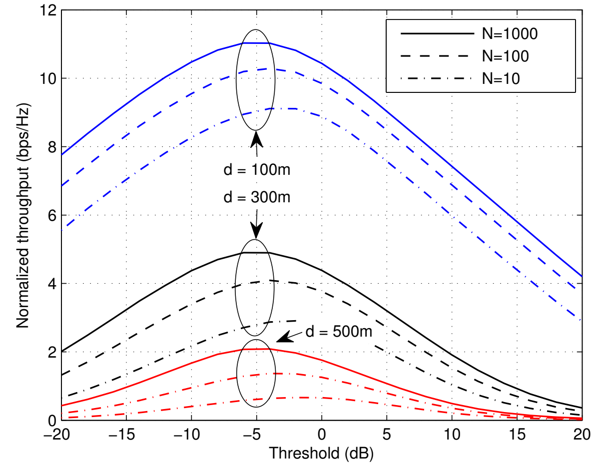

Fig. 3. Normalized throughput of CS-ICI vs. threshold ($\gamma_{\rm th}$).

For the channel model, the 3GPP dual-strip model in [18] (Table A. 2.1.1.2-8) is used, where for a given distance of d between a user and a BS, the large-scale path-loss model is expressed as

$$PL(\text{dB}) = 15.3 + 37.6\log_{10}(d). \tag{20}$$

We observe a user having a distance of d away from BS 0 through the direction of Arrow 1 as in Fig. 1. The simulation is performed for a long time that the user being observed is selected by BS 0 at least in 10^4 slots.

Fig. 2 shows the normalized throughput of CS-SE over varying the multiplexing factor θ. We can observe that there exists the optimal multiplexing factor that maximizes the normalized throughput. For a given user location, the optimal multiplexing factor is nearly constant with different population size. However, the optimal multiplexing factor varies much over different user locations. Hence, the system should store different multiplexing factors for users having different locations. The optiimal multiplexing factor becomes smaller as the the distance d increases. This is because a user having a larger distance away from its serving BS may suffer more from inter-cell interference as it is closer to some neighbor cells and, therefore, has to reduce the transmission data rate more.

Fig. 3 shows the normalized throughput of CS-ICI over varying the threshold $\gamma_{\rm th}$. We can see that the optimal threshold that maximizes the normalized throughput is almost constant around -5dB for diverse user locations and population sizes. Although $\gamma_{\rm th} = -5$dB is not the exact optimal threshold, the obtained throughput is very close to the maximum throughput. This property greatly simplifies the operation of CS-ICI as a single threshold is enough to accommodate diverse networks scenarios.

Fig. 4 shows the normalized throughput over increasing the user population N when the user being observed has the distances of 300m and 500m. The throughput of Round-robin scheduling is also presented for a comparison. The optimal multiplexing factor, which is numerically searched as in Fig. 2, is applied for the Round-robin scheduling. For CS-SE and CS-ICI, the optimal multiplexing factor or threshold is applied to observe their potentials. Despite increasing the population size, the Round-robing scheduling shows constant throughput as it cannot exploit the multi-user diversity. Both throughputs of CS-SE and CS-ICI increase as N increases, which demonstrates their ability in exploiting the multi-user diversity. However, the proposed CS-ICI shows a faster throughput increment as N increases. Moreover, a tradeoff between CS-SE and CS-ICI can be observed: CS-ICI tends to show a better performance with a larger N. When the population size is large, with high probability CS-ICI selects a user who has not scaled down its transmit power due to the multi-user diversity. Therefore, the CS-ICI shows a better throughput performance than CS-SE as CS-ICI controls the inter-cell interference. On the other hand, when the population size is small, CS-ICI may select a user who has scaled down its transmit power to meet the inference requirement. Hence, CS-ICI may show a worse performance than CS-SE as it has small transmit power. This phenomenon happens more frequently for cell edge users because they are close to neighbor cells which results in the frequent power reduction with CS-ICI. We also present the throughput of CS-ICI with setting a fixed threshold of $\gamma_{\rm th} = -5$dB. As expected, it shows very closed performance as CS-ICI with the optimal threshold.

Fig. 5 shows the normalized throughput over varying the distance of the user being observed when $N = 100$. CS-ICI tends to show a better throughput performance than CS-SE when the user is close to the cell center. Compared to the cell center users, the cell edge users may reduce their transmit power more frequently with CS-ICI and, therefore, obtain less throughput enhancement. Although CS-SE may show a better performance than CS-ICI for the cell edge users, it should be noted that the data rate selection of CS-SE has a higher implementation complexity as the optimal multiplexing factor

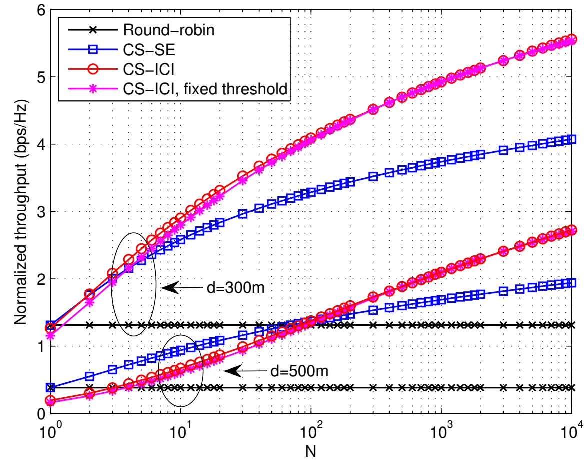

Fig. 4. Normalized throughput vs. N.

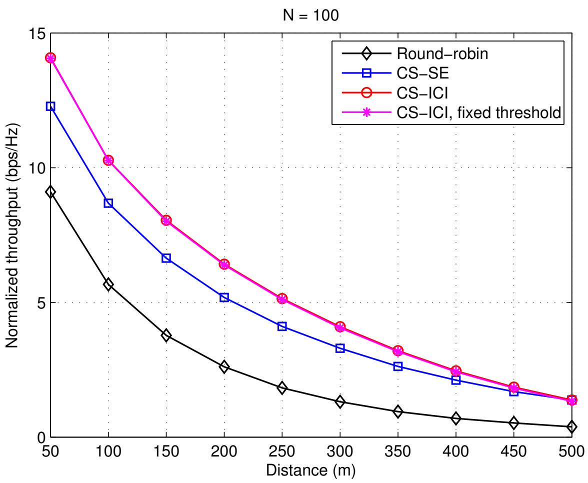

Fig. 5. Normalized throughput vs. user location ($N = 100$).

changes by the user locations while CS-ICI only needs a single threshold for any user location.

VI. Conclusion

In this paper, we proposed a CDF-based scheduling in the presence of inter-cell interference for uplink multi-cell networks, which not only efficiently exploits multi-user diversity but also satisfies resource-based fairness among users. The proposed scheduling enables each user to adjust its transmit power if its generating interference to other BSs exceeds a pre-determined threshold. Extensive simulation results show that a fixed threshold for the proposed scheduling is enough to accommodate diverse population sizes and user locations. Moreover, it is shown that the proposed scheduling achieves the double-logarithmic growth of the normalized user throughput when the number of users in a cell tends to infinity, which is the same throughput scaling obtained in a signle cell network without inter-cell interference.

Acknowledgement

This work was supported by the Canadian Natural Sciences and Engineering Research Council (NSERC) through grant STPGP 396756 and funded by the MSIP (Ministry of Science, ICT & Future Planning), Korea in the ICT R&D Program 2013.

References

[1] R. Knopp and P. A. Humblet, "Information capacity and power control in single cell multiuser communications," *in Proc. IEEE International Conference on Communications (ICC)*, pp. 331–335, Jun. 1995.

[2] D. N. C. Tse, "Optimal power allocation over parallel Gaussian broadcast channels," *in Proc. IEEE International Symposium on Information Theory (ISIT)*, p. 27, Jun.-Jul. 1997.

[3] S. Borst and P. Whiting, "Dynamic rate control algorithms for HDR throughput optimization," *in Proc. IEEE International Conference on Computer Communications (INFOCOM)*, pp. 976–985, Aug. 2001.

[4] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic beamforming using dumb antennas," *IEEE Trans. Inf. Theory*, vol. 48, no. 6, pp. 1277–1294, Jun. 2002.

[5] N. Sharma and L. H. Ozarow, "A study of opportunism for multiple-antenna systems," *IEEE Trans. Inf. Theory*, vol. 51, no. 5, pp. 1804–1814, May 2005.

[6] X. Liu, E. K. P. Chong, and N. B. Shroff, "Opportunistic transmission scheduling with resource-sharing constraints in wireless networks," *IEEE J. Sel. Areas Commun.*, vol. 19, no. 10, pp. 2053–2064, Oct. 2001.

[7] X. Qin and R. Berry, "Opportunistic splitting algorithms for wireless networks with hegerogeneous users," *Proc. Conf. Inform. Sciences Systems (CISS)*, Mar. 2004.

[8] T. Bonald, "A score-based opportunistic schedulerr for fading radio channels," *Proc. European Wireless*, 2004.

[9] D. Park, H. Seo, H. Kwon, and B. G. Lee, "Wireless packet scheduling based on the cumulative distribution function of user transmission rate," *IEEE Trans. Commun.*, vol. 53, no. 11, pp. 1919–1929, 2005.

[10] Y. Huang and B. D. Rao, "Random beamforming with heterogeneous users and selective feedback: Individual sum Rate and individual scaling laws," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2080–2090, May 2013.

[11] U. Ben-Porat, A. Bremler-Barr, and H. Levy, "On the exploitation of CDF based wireless scheduling," *in Proc. IEEE International Conference on Computer Communications (INFOCOM)*, pp. 2821–2825, Apr. 2009.

[12] H. Jin, B. C. Jung, and V. C. M. Leung, "A novel feedback reduction technique for cellular downlink with CDF-based scheduling," *in Proc. IEEE International Conference on Communications (ICC)*, pp. 4015–4055, Jun. 2013.

[13] B. C. Jung, D. Park, and W.-Y. Shin, "Opportunistic interference mitigation achieves optimal degrees-of-freedom in wireless multi-cell uplink networks," *IEEE Trans. Commun.*, vol. 60, no. 7, pp. 1935–1944, July 2012.

[14] H. J. Yang, W.-Y. Shin, B. C. Jung, and A. Paulraj, "Opportunistic interference alignment for MIMO interfering multiple access channels," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2180–2192, May 2013.

[15] W.-Y. Shin, D. Park, and B. C. Jung, "Can one achieve multiuser diversity in uplink multi-cell networks?" *IEEE Trans. Commun.*, vol. 60, no. 12, pp. 3535–3540, Dec. 2012.

[16] M. Sharif and B. Hassibi, "On the capacity of MIMO broadcast channels with partial side information," *IEEE Trans. Inf. Theory*, vol. 51, no. 2, pp. 506–522, Feb. 2005.

[17] H. Jin, B. C. Jung, and V. C. M. Leung, "Fundamental limits of CDF-based scheduling: throughput, fairness, and feedback overhead," *IEEE/ACM Trans. Netw. (Submitted).*

[18] *E-UTRA: Further advancements for E-UTRA physical layer aspects*, 3GPP TR 36.814 V9.0.0 Std., Mar. 2010.