Enhancing User Fairness in Non-orthogonal Access with Successive Interference Cancellation for Cellular Downlink

Junpei Umehara†, Yoshihisa Kishiyama‡, and Kenichi Higuchi†(*)
†Graduate School of Science and Technology, Tokyo University of Science
‡Radio Access Network Development Department, NTT DOCOMO, INC.
E-mail: (*)higuchik@rs.noda.tus.ac.jp

Abstract—**Aiming at a better tradeoff between the system frequency efficiency measured by the mean user throughput and the user fairness measured by the cell-edge user throughput, we propose applying fractional frequency reuse (FFR) and weighted proportional fair (PF)-based multiuser scheduling to non-orthogonal access with a successive interference canceller (SIC) in the cellular downlink. We also propose a frequency block access policy for cell-interior and cell-edge user groups in FFR, which are appropriate for non-orthogonal access with the SIC. The optimum power is allocated to the non-orthogonally multiplexed users in conjunction with the weighted multiuser PF scheduler. Extensive simulation results show that the proposed non-orthogonal access scheme with the SIC significantly enhances the system frequency efficiency and user fairness at the same time compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems.**

I. Introduction

In the 3rd generation mobile communication systems such as W-CDMA or cdma2000, non-orthogonal access based on direct sequence-code division multiple access (DS-CDMA) is widely used in the downlink. The receiver uses simple single-user detection such as the Rake receiver. Orthogonal access based on orthogonal frequency division multiple access (OFDMA) is adopted in the 3.9 and 4th generation mobile communication systems such as LTE [1] and LTE-Advanced [2, 3]. Orthogonal access is a reasonable choice for achieving good system-level throughput performance in packet-domain service by using channel-aware time- and frequency-domain scheduling with simple single-user detection.

However, for systems beyond 4G, the system throughput and user fairness must be enhanced further considering the recent exponential increase in mobile traffic and the need for enhanced delay-sensitive high-volume services such as video-streaming and cloud computing. To accommodate such requirements, non-orthogonal access with advanced transmission/reception techniques such as dirty paper coding (DPC) or using a successive interference canceller (SIC) [4, 5], which is different from the 3rd generation mobile communication system, represent promising candidates as a downlink wireless access scheme for systems beyond those mentioned above. In this investigation, we use the SIC for inter-user interference cancellation, since DPC is difficult to implement and sensitive to the error in the channel state information feedback.

An attractive feature of non-orthogonal access with the SIC is that it improves user fairness with regard to the achievable user throughput. This is because all users can use the overall transmission bandwidth irrespective of the channel conditions in non-orthogonal access, while orthogonal access must restrict the bandwidth assignment to the users under poor channel conditions in order to achieve a sufficiently high total (mean) user throughput. In [6], members of our research group showed the system-level throughput gain (in terms of system frequency efficiency and user fairness) by using non-orthogonal access with the SIC relative to orthogonal access, assuming universal frequency reuse and proportional fair (PF)-based resource (bandwidth and transmission power) allocations [7-9]. The results in [6] indicate that by using non-orthogonal access with the SIC a large user throughput gain is observed at the users near the base station when a pure PF scheduler and universal frequency reuse are assumed. As a result, compared to the system frequency efficiency gain, the gain in the cell-edge user throughput is rather limited.

Aiming at further improving the cell-edge user throughput by translating the throughput gain observed at the vicinity of the base station to a gain at the cell edge, we propose applying fractional frequency reuse (FFR) and weighted PF-based multiuser scheduling to non-orthogonal access with the SIC in the cellular downlink. The inter-cell interference dominates the system-level throughput performance in the cellular system. This is especially true for users near the cell edge who receive the highest level of inter-cell interference. A promising approach for mitigating the inter-cell interference problem is employing frequency reuse between neighboring cells. In particular, FFR, e.g., in [11−14] which allows users under different channel conditions to enjoy different reuse factors, achieves a tradeoff between the frequency bandwidth utilization per cell and the impact of inter-cell interference. In the paper, we propose a frequency block access policy for cell-interior and cell-edge user groups in FFR, which are especially appropriate for non-orthogonal access with the SIC.

In inter-cell interference coordinated cells using FFR, the weighted PF scheduler [10] further improves the cell-edge user throughput at the cost of a moderate loss in the system frequency efficiency. The weighting factor of the weighted PF scheduler controls the tradeoff between the system frequency efficiency and user fairness. We allocate the optimum power to non-orthogonally multiplexed users in conjunction with the weighted multiuser PF scheduler.

The remainder of the paper is organized as follows. Section II describes the basic system model employing non-orthogonal access with the SIC and FFR. Section III describes multiuser scheduling and power allocation methods based on the weighted PF scheduler. Then, Section IV presents simulation results on the system-level throughput and a comparison to orthogonal access. Finally, Section V concludes the paper.

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II. SYSTEM MODEL

A. FFR

Fig. 1 shows a typical FFR method called soft FFR, which is assumed in the paper. The overall system transmission bandwidth is divided into two parts: a frequency band with priority given to cell-edge users (edge band hereafter) and that with priority given to cell-interior users (inner band hereafter). The bandwidth for the edge band is assumed to be 1/3 of the overall system transmission bandwidth. Among the three neighboring cells, the edge bands do not overlap as indicated in Fig. 1. The transmission power density for the edge band is set to be larger than that for the inner band. These settings yield inter-cell interference coordination [14] for the edge band since the increased transmission power density for the edge band and reduced transmission power density for the inner band of neighboring cells results in a better signal-to-inter-cell interference power ratio at the edge band.

The users within a cell are categorized into cell-interior and cell-edge user groups based on the average path loss (distance-dependent loss and shadowing loss) between the user and the serving base station. In most relevant literature, e.g., [11−14], it is assumed that the edge band is dedicated to only the cell-edge user group and the inner band is used only by the cell-interior users. However, this hard partitioning policy in frequency band access for respective user groups has several drawbacks. First, when we assume channel-aware scheduling such as when using a PF-based scheduler, the multiuser diversity gain is decreased since only a limited set of users can access the respective bands. Furthermore, when we assume non-orthogonal access with the SIC, we achieve gains such as better bandwidth and power utilization within a cell especially when users experiencing good channel conditions are multiplexed with those experiencing bad channel conditions in the same frequency block [5]. The hard partitioning policy will prevent this type of user multiplexing. Therefore, in the paper, we consider a *soft* frequency block access policy for cell-interior and cell-edge user groups in FFR. The details of this policy along with the channel-aware scheduling are presented in Section III.

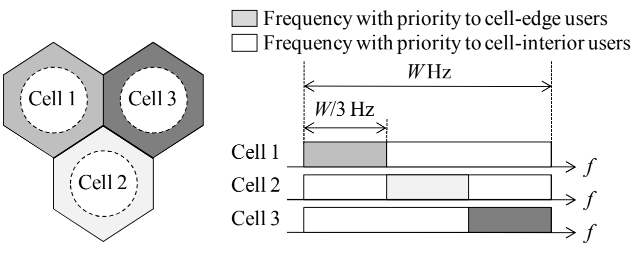


Figure 1. Spectrum usage in soft FFR.

B. Non-orthogonal Access with SIC

We assume orthogonal frequency division multiplexing (OFDM) signaling with a cyclic prefix, although we consider non-orthogonal user multiplexing. Therefore, the inter-symbol interference and inter-carrier interference are perfectly eliminated assuming that the length of the cyclic prefix is sufficiently long so that it covers the entire multipath delay spread.

In the paper, the number of transmitter antennas at the base station is assumed to be one. The number of receiver antennas at the user terminal is N_r. The number of users per cell is K. There are B frequency blocks and the bandwidth of the frequency block is W. The set of all frequency block indices is denoted as $\mathcal{X} = \{1, 2, ..., B\}$. The sets of frequency blocks within the edge band and inner band of the base station of interest are denoted as $\mathcal{X}_{\text{edge}}$ and $\mathcal{X}_{\text{inner}}$, respectively. It is assumed that $|\mathcal{X}_{\text{edge}} \cap \mathcal{X}_{\text{inner}}| = 0$ and $\mathcal{X}_{\text{edge}} \cup \mathcal{X}_{\text{inner}} = \mathcal{X}$. The transmission power per subcarrier at the edge band and inner band are P_{edge} and P_{inner}, respectively.

Let us assume that the multiuser scheduler schedules set $\mathcal{S}_b = \{i_b(1), i_b(2), ..., i_b(m_b)\}$ of users to frequency block b ($1 \le b \le B$), where $i_b(l)$ indicates the l-th ($1 \le l \le m_b$) user index scheduled at frequency block b and m_b denotes the number of scheduled users at frequency block b. In this section, time index t is omitted for simplicity. At the base station transmitter, each of the $i_b(l)$-th user information bit sequences is independently channel coded and modulated. Transmit signal x_b at a certain subcarrier of frequency block b is a simple summation of the $i_b(l)$-th coded modulation symbol $s_b(i_b(l))$. Thus, $s_b(i_b(l))$ of all m_b users is superposition coded as

$$x_b = \sum\nolimits_{l=1}^{m_b} \sqrt{p_b(i_b(l))}\, s_b(i_b(l)), \tag{1}$$

where $\mathrm{E}[|s_b(i_b(l))|^2] = 1$ and $p_b(i_b(l))$ is the allocated transmission power for user $i_b(l)$ at frequency block b. The set of $p_b(i_b(l))$ is constrained as

$$\sum\nolimits_{l=1}^{m_b} p_b(i_b(l)) = \begin{cases} P_{\text{edge}}, & b \in X_{\text{edge}} \\ P_{\text{inner}}, & b \in X_{\text{inner}} \end{cases}. \tag{2}$$

The N_r-dimensional received signal vector of user $i_b(l)$ at a certain subcarrier of frequency block b is represented as

$$\mathbf{y}_b(i_b(l)) = \mathbf{h}_b(i_b(l)) x_b + \mathbf{w}_b(i_b(l)), \tag{3}$$

where $\mathbf{h}_b(i_b(l))$ is the N_r-dimensional channel coefficient vector of user $i_b(l)$ at frequency block b, which includes distance-dependent loss, shadowing loss, and instantaneous fading coefficients. For simplicity, we assume here that the instantaneous fading coefficients are kept constant within a frequency block. Term $\mathbf{w}_b(i_b(l))$ is the N_r-dimensional noise and inter-cell interference vector of user $i_b(l)$ at frequency block b. We assume that the receiver performs maximum ratio combining (MRC) on $\mathbf{y}_b(i_b(l))$ as

$$\begin{aligned} \tilde{y}_b(i_b(l)) &= \mathbf{h}_b^H(i_b(l)) \mathbf{y}_b(i_b(l)) / \|\mathbf{h}_b\| \\ &= \|\mathbf{h}_b(i_b(l))\| x_b + \mathbf{h}_b^H(i_b(l)) \mathbf{w}_b(i_b(l)) / \|\mathbf{h}_b\|, \\ &= \sqrt{g_b(i_b(l))}\, x_b + z_b(i_b(l)) \end{aligned} \tag{4}$$

where $g_b(i_b(l)) = \|\mathbf{h}_b(i_b(l))\|^2$ is the equivalent channel gain after MRC and $z_b(i_b(l))$ is the noise and inter-cell interference term after MRC. The average power of $z_b(i_b(l))$ is denoted as $n_b(i_b(l)) = \mathrm{E}[|z_b(i_b(l))|^2]$.

With the SIC, the decoding order should be in order of the increasing channel gain normalized by the noise and inter-cell interference power, $g_b(i_b(l))/n_b(i_b(l))$. Thus, user $i_b(l)$ can remove the inter-user interference from user j whose $g_b(j)/n_b(j)$ is lower than $g_b(i_b(l))/n_b(i_b(l))$. Therefore, the throughput of user $i_b(l)$ at frequency block b assuming the scheduler schedules user set $\mathcal{S}_b$ is represented as

$$R_b(i_b(l)\,|\,\mathcal{S}_b) = W\log_2\left(1+\frac{g_b(i_b(l))p_b(i_b(l))}{\sum_{j\in\mathcal{S}_b,\frac{g_b(i_b(l))}{n_b(i_b(l))}<\frac{g_b(j)}{n_b(j)}} g_b(i_b(l))p_b(j)+n_b(i_b(l))}\right). \quad (5)$$

III. Multiuser Scheduling and Power Allocation

A. Multiuser Scheduling Based on Weighted PF and Soft Frequency Block Access Policy

In non-orthogonal access with the SIC, the scheduler can simultaneously allocate a frequency block to more than one user. The scheduling policy greatly affects the system efficiency (measured by, for example, the total average user throughput) and user fairness (measured by, for example, the cell-edge average user throughput). The PF scheduler [7, 8] is known to achieve a good tradeoff between them by maximizing the product of the average user throughput among users within a cell. In [9], the multiuser version of the PF scheduler is presented. In the paper, a modified version of the method in [9] is used for the FFR with a hard or soft frequency block access policy for cell-interior and cell-edge user groups.

The average user throughput of user k per frequency block is defined as

$$T(k;t+1)=\left(1-\frac{1}{t_c}\right)T(k;t)+\frac{1}{t_c}\left(\frac{1}{B}\sum_{b=1}^{B}R_b\left(k;t\right)\right), \quad (6)$$

where t denotes the time index representing the subframe index. Parameter t_c defines the time horizon for throughput averaging. We assume the t_c of 100 with the subframe length of 1 ms in the following evaluation (thus 100-ms averaged user throughput is measured) according to the assumptions in [1] and [2]. Term $R_b(k;\,t)$ is the throughput of user k in frequency block b at time instance t. Throughput $R_b(k;\,t)$ is calculated using (5) and is zero if user k is not scheduled in frequency block b.

Under proportional fairness, the multiuser scheduling policy that maximizes the product of the average user throughput among users within a cell selects user set $\mathcal{S}_b$ according to the following criteria [9].

$$f_b(\mathcal{S})=\prod_{k\in\mathcal{S}}\left(1+\frac{R_b(k\,|\,\mathcal{S};t)}{(t_c-1)T^{\gamma}(k;t)}\right) \text{ and} \quad (7)$$

$$\mathcal{S}_b=\arg\max_{\mathcal{S}} f_b(\mathcal{S}) \quad (8)$$

Here, γ ($\gamma \geq 0$) is the weighting factor introduced in [10]. The γ of one corresponds to the pure PF scheduler and the γ of greater than one tends to achieve better user fairness at the cost of reduced system efficiency. Term $f_b(\mathcal{S})$ is the scheduling metric for user set $\mathcal{S}$, and the user set $\mathcal{S}$ that maximizes the scheduling metric is selected.

In FFR, the scheduling metric is affected by the frequency block access policy. The sets of users categorized into cell-edge and cell-interior user groups are denoted as $\mathcal{K}_{\text{edge}}$ and $\mathcal{K}_{\text{inner}}$, respectively. In the conventional hard frequency block access policy, $R_b(k;\,t)$ is set to zero in the calculation of (7) when $k \in \mathcal{K}_{\text{edge}}$ and $b \in \mathcal{X}_{\text{inner}}$, or $k \in \mathcal{K}_{\text{inner}}$ and $b \in \mathcal{X}_{\text{edge}}$. In the proposed soft frequency block access policy, users are partitioned by introducing a priority coefficient in (7).

$$f_b(\mathcal{S})=\prod_{k\in\mathcal{S}}\left(1+\frac{\alpha_b(k)R_b(k\,|\,\mathcal{S};t)}{(t_c-1)T^{\gamma}(k;t)}\right) \text{ and} \quad (9)$$

$$\alpha_b(k)=\begin{cases}\alpha_{\text{edge}},\ b\in X_{\text{inner}}, k\in K_{\text{edge}}\\ \alpha_{\text{inner}},\ b\in X_{\text{edge}}, k\in K_{\text{inner}}\\ 1,\ \text{otherwise}\end{cases} \quad (10)$$

Parameters α_{edge} and α_{inner} ($0 \leq \alpha_{\text{edge}}, \alpha_{\text{inner}} \leq 1$) are the soft priority coefficient of the cell-edge users in the inner band and that of the cell-interior users in the edge band, respectively. When α_{edge} and α_{inner} are both zero, this situation corresponds to the conventional hard frequency block access policy. By setting α_{edge} and α_{inner} to greater than zero, the proposed soft frequency block access policy increases the multiuser diversity gain and the effect of the non-orthogonal user multiplexing along with the SIC.

B. Transmission Power Allocation

The remaining problem is the transmission power allocation to the scheduled users. In non-orthogonal access with the SIC, the power allocated to a certain user affects the achievable throughput of not only that user but also other users due to inter-user interference. Therefore, the transmission power allocation and multiuser scheduling are related to each other. In the paper, for each candidate set of users, $\mathcal{S}$, the optimal power allocation is conducted so that the scheduling metric, $f_b(\mathcal{S})$, is maximized.

When $t_c >> 1$, which is valid in the paper where $t_c = 100$, (9) can be approximated as (after removing several constants)

$$f_b(\mathcal{S})\approx\sum_{k\in\mathcal{S}}\frac{\alpha_b(k)}{T^{\gamma}(k;t)}R_b(k\,|\,\mathcal{S};t)\cdot \quad (11)$$

Equation (11) is a weighted sum of the instantaneous user throughput, $R_b(k|\mathcal{S};\,t)$, where the weighting factor for user k is $\alpha_b(k)/T^{\gamma}(k;\,t)$. Therefore, for given candidate scheduling policy $\mathcal{S}$, the metric can be maximized by the power allocation, which maximizes the weighted sum of the instantaneous user throughput. We use the iterative water-filling power allocation algorithm [15] that achieves the maximum weighted sum of the user throughput utilizing the uplink-downlink duality presented, for example, in [16]. Please refer to [15] for details regarding the power allocation algorithm.

IV. Simulation Results

A. Simulation Parameters

We evaluated the distribution of the user throughput in a multi-cell downlink. Table I gives the simulation parameters. These parameters are based on [17]. A 19-cell model with a hexagonal grid is employed. The inter-site (base station) distance is 500 m. The number of users per cell, K, is set to 30. The location of the user terminal in each cell is randomly assigned with a uniform distribution. Parameters W and B are set to 180 kHz [1] and 24, respectively (the overall transmission bandwidth is 4.32 MHz). The transmission power at the base station is 40 dBm. For FFR, eight frequency blocks, which are non-overlapped between neighboring cells are used for the edge band. The transmission power density of the edge band is set to β-dB higher than that of the inner band. The value of β is parameterized in the following evaluation. Among 30 users per cell, 10 users are categorized into the cell-edge user group based on the average path loss to the serving base station.

In the propagation model, we took into account distance-dependent path loss with the decay factor of 3.76; lognormal shadowing with the standard deviation of 8 dB and the correlation of 0.5 among sites; and 6-path Rayleigh fading with the rms delay spread of 1 μs and the maximum Doppler frequency of 55.5 Hz. The number of receiver antennas at the user terminal, N_r, is set to two. The receiver noise density of the user terminal is set to −169 dBm/Hz. The radio resource allocation is updated in 1-ms intervals. The user throughput averaged over 100 ms is measured. The user throughput is calculated based on the Shannon formula with the maximum limit of 6 b/s/Hz (corresponding to 64QAM). The maximum number of non-orthogonally multiplexed users per frequency block in non-orthogonal access is limited to three considering the performance gain and the complexity in the SIC. The performance of orthogonal access, where the maximum number of non-orthogonally multiplexed users per frequency block is limited to one, is also evaluated for comparison. In the following, we simply denote 100-ms averaged user throughput as the user throughput. The user throughput value at the cumulative probability of 5% is denoted as the cell-edge user throughput [1, 2], apart from the definition of the cell-edge user group in FFR.

TABLE I. SIMULATION PARAMETERS

Cell layout		Hexagonal 19-cell model
Inter-site distance		0.5 km
Overall transmission bandwidth		4.32 MHz
Resource block bandwidth		180 kHz
Number of resource blocks		24
Number of user terminals per cell		30
BS transmitter antenna	Number of antennas	1
	Antenna gain	14 dBi
User terminal receiver antenna	Number of antennas	2
	Antenna gain	0 dBi
Base station transmission power		40 dBm
Distance-dependent path loss		$128.1 + 37.6 \log_{10}(r)$ dB, r: kilometers
Log-normal shadowing		Standard deviation = 8 dB Correlation among cells = 0.5
Instantaneous fading		Six-path Rayleigh, rms delay spread = 1 μs, f_D = 55.5 Hz
Receiver noise density		-169 dBm/Hz
Scheduling interval		1 ms
Throughput calculation		Based on Shannon formula (Max. 6 b/s/Hz)
Averaging interval of user throughput		100 ms (t_c = 100)

B. Simulation Results

Fig. 2 shows the cell-edge and mean user throughput as a function of β. Both α_{edge} and α_{inner} are set to 1.0. Weighting factor γ is set to 1.0. The arithmetic mean throughput, which is the basic performance measure of system efficiency in LTE and LTE-advanced [1, 2], and the geometric mean throughput, which may be a good system performance measure taking into account the system efficiency and user fairness simultaneously, are presented. By using an appropriate setting for β, the cell-edge user throughput is significantly increased with the proposed soft frequency block access policy. In non-orthogonal access with the SIC, although universal frequency reuse (β = 0 dB) is the best from the mean user throughput point of view, the use of β greater than 0 dB is beneficial for enhancing the cell-edge user experience while maintaining the advantage of the mean user throughput compared to orthogonal access. In orthogonal access, a β of greater than 0 dB is also beneficial in improving the mean user throughput since the throughput of orthogonal access is dominated by inter-cell interference (there is no intra-cell interference in contrast to non-orthogonal access).

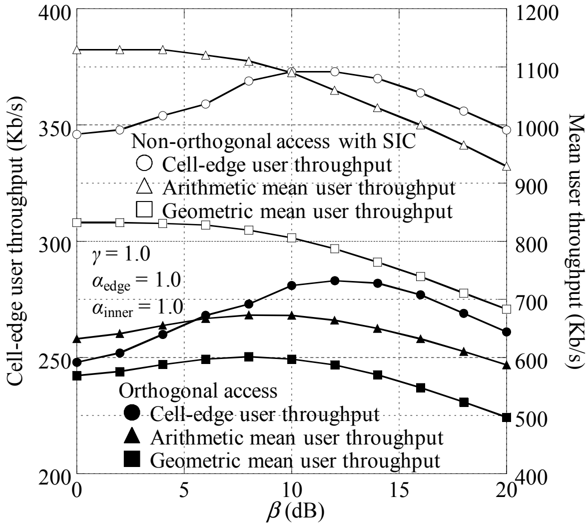
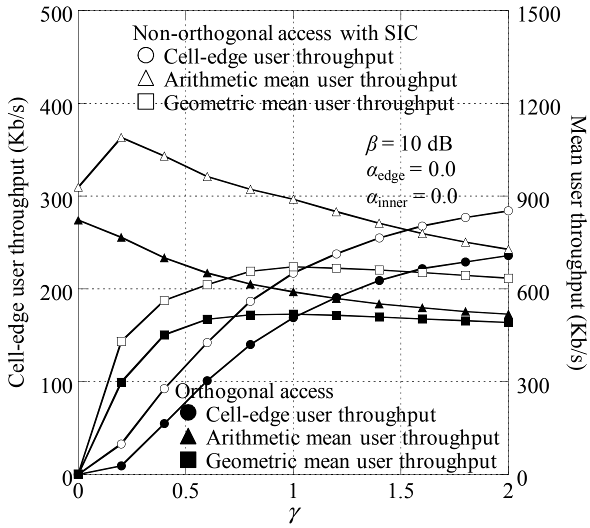


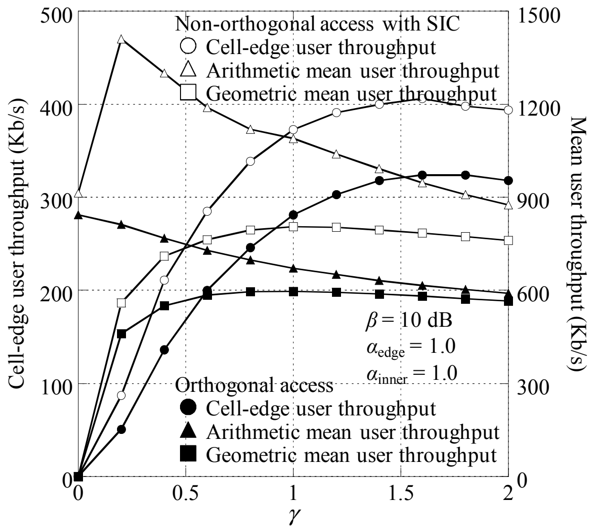
Figure 2. Cell-edge and mean user throughput as a function of β.

Figs. 3(a) and 3(b) show the cell-edge and mean user throughput as a function of γ, for the case with $\alpha_{\text{edge}} = \alpha_{\text{inner}}$ = 0.0 (conventional hard access policy) and $\alpha_{\text{edge}} = \alpha_{\text{inner}}$ = 1.0 (proposed soft access policy), respectively. Parameter β is set to 10 dB. When comparing Figs. 3(a) and 3(b), we can clearly see that the proposed soft access policy achieves higher user throughput than the conventional hard access policy. The effect of the proposed access policy is especially significant for non-orthogonal access with the SIC. The gain comes from the increased multiuser diversity gain and the effective non-orthogonal user multiplexing. For maximizing the geometric mean throughput, γ of one (thus, pure PF) is optimal. However, as γ is increased from one, the cell-edge user throughput is increased at the cost of reduced arithmetic mean user throughput. This is because as γ is increased, the scheduling metric is dominated by the average user throughput, $T(k; t)$, which results in an increased number of transmission opportunities for the cell-edge users whose $T(k; t)$ is low.

Fig. 4 shows the user throughput gain by using non-orthogonal access with the SIC relative to orthogonal access for the respective user coverage positions (0 indicates the cell edge and 1 indicates the vicinity of the base station). The proposed soft access policy is assumed. In the orthogonal access, β of 8 dB and γ of 1.0 are assumed to maximize the arithmetic mean user throughput. For non-orthogonal access with the SIC, we tested three cases: the universal frequency reuse with pure PF (β = 0 dB and γ = 1.0), FFR with pure PF (β = 10 dB and γ = 1.0), and FFR with weighted PF (β = 10 dB and γ = 1.6). Fig. 4 shows that the user throughput gain of greater than 1 is observed for the entire region of the user coverage position. By employing the FFR and weighted PF, the cell-edge user throughput gain is further increased, which will be very beneficial in accommodating future traffic demands. The property of the monotonously decreasing user throughput gain against the user coverage position is advantageous from the user fairness viewpoint.



(a) $\alpha_{\mathrm{edge}} = \alpha_{\mathrm{inner}} = 0.0$



(b) $\alpha_{\mathrm{edge}} = \alpha_{\mathrm{inner}} = 1.0$

Figure 3. Cell-edge and mean user throughput as a function of γ.

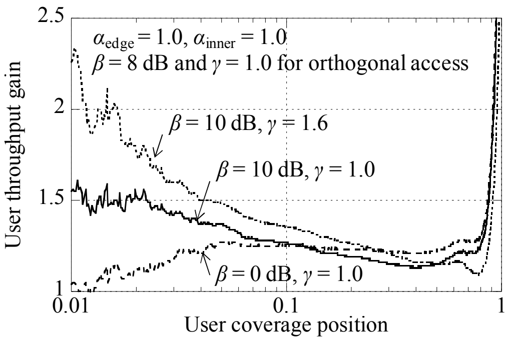


Figure 4. User throughput gain.

V. CONCLUSION

This paper investigated applying FFR and weighted PF-based multiuser scheduling to non-orthogonal access with the SIC in the cellular downlink, aiming at further enhancing the user fairness. Computer simulation results show the effectiveness of the proposed soft frequency block access policy for cell-interior and cell-edge user groups in FFR along with the channel-aware scheduling. The simulation results indicate that non-orthogonal access with the SIC along with FFR and weighted PF can significantly enhance the system-level throughput performance compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems. The enhancement to the cell-edge user experience is especially significant, which will be very beneficial in accommodating future traffic demands. Although we assume the Shannon-theoretic throughput measure, performance evaluation assuming realistic a channel code, QAM data modulation, and residual interference in the SIC process is needed for a more concrete conclusion.

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