Non-orthogonal Access with SIC in Cellular Downlink for User Fairness Enhancement

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Abstract—**This paper investigates the enhancement of cell-edge user throughput by using non-orthogonal access with a successive interference canceller (SIC) in the cellular downlink compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems. Since both the total user throughput and cell-edge user throughput are important in a real system, we compare the cell-edge user throughput while subject to the same total user throughput. The optimum resource allocation in terms of bandwidth and transmission power for each user is assumed for the respective access schemes based on the instantaneous channel conditions. The evaluation results show that non-orthogonal access with a SIC significantly enhances the cell-edge user throughput (thus user fairness) compared to orthogonal access while achieving the same total user throughput in the context of the cellular downlink, which can yield some insights regarding the direction of the wireless access scheme for the systems beyond IMT-Advanced.**

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. 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, WiMAX, LTE-Advanced, and IEE802.16m. However, non-orthogonal access can again be a promising candidate as a downlink wireless access scheme for systems beyond those mentioned above, which is the purpose of this study. To make non-orthogonal access promising, it should be used with advanced transmission/reception techniques such as dirty paper coding (DPC) or using a successive interference canceller (SIC) [1, 2], which is different from the 3rd generation mobile communication system.

The fairness of the achievable user throughput within a cell becomes more important in future mobile communication systems, in which it is expected that the enhanced delay-sensitive high-volume service such as video-streaming and cloud computing will be supported. Let us assume that there is user i with probability f_i and his/her achievable user throughput per hertz is R_i. The average user throughput R_{avg} is $\Sigma_i\{f_iR_i\}$. If all users want to enjoy service with the data rate of X with the system bandwidth of W_{s}, the required bandwidth of each user is X/R_i. Therefore, the maximum number of accommodated users K becomes $(W_{\mathrm{s}}/X)/\Sigma_i\{f_i/R_i\}$, since $\Sigma_i\{f_iK(X/R_i)\} \leq W_{\mathrm{s}}$ is required. K is maximized when R_i is constant for a given average user throughput R_{avg}. This indicates the importance of the user fairness regarding the achievable user throughput.

We believe that the main purpose (attractive feature) of non-orthogonal access with advanced transmission/reception techniques is to improve 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 (average) user throughput [2]. In a real system, both the total user throughput and cell-edge user throughput are important performance metrics, e.g., in [3]. Although there are several studies that compare orthogonal and non-orthogonal access in the context of a cellular system [4-7], most of these studies consider only one of the two metrics. Therefore, in this paper, we compare the cell-edge user throughput of the non-orthogonal access with a SIC and that of orthogonal access in the cellular downlink, while subject to the same total user throughput. The optimum resource allocation in terms of the bandwidth and transmission power for each user based on the instantaneous channel conditions is assumed for the respective access schemes for fair comparison, considering the trend in packet domain switching with fast link adaptation in the latest wireless communication systems. Furthermore, the performance of non-orthogonal access with a SIC is compared to that for orthogonal access with a proportional fair (PF) scheduler [8], since the combination of orthogonal access and the PF scheduler is widely used in the latest mobile communication systems.

The remainder of the paper is organized as follows. First, Section II describes the system model and throughput calculations based on the optimum resource allocation. Then, Section III shows numerical results on the cell-edge user throughput. Finally, Section IV concludes the paper.

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II. System Model and Throughput Evaluation With Optimum Resource Allocation

We assume orthogonal frequency division multiplexing (OFDM) signaling with a cyclic prefix, irrespective of the access schemes. 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. The number of transmitter antennas at the base station and that of the receiver antennas at the user terminal are both one. The number of users per cell is K. There are B frequency blocks and the bandwidth of the frequency block is W. The path gain (square of the instantaneous channel coefficient) of the k-th ($1 \le k \le K$) user at the b-th ($1 \le b \le B$) frequency block is denoted as $h_{k,b}$. The transmission power of the base station is P. Furthermore, we assume that the transmission power density is fixed to P/BW irrespective of the access schemes. One merit of the fixed transmission power density is that we can obtain a static profile of the inter-cell interference. Therefore, there is no need for cooperation from neighboring base stations for the optimum radio resource allocation. A drawback may be the degraded achievable throughput because the waterfilling principle is not utilized [2]. However, since our preliminary simulation results indicate that the throughput degradation on average is very small in a typical cellular scenario, we assume fixed transmission power density in the paper.

In the paper, we simultaneously consider two important system-level performance metrics, the total user throughput and cell-edge user throughput. The total user throughput is maximized when each frequency block is assigned to a user experiencing the highest signal-to-interference plus noise power ratio (SINR) among candidate users at the frequency block [2]. Therefore, with the fixed transmission power density assumption, the maximum total user throughput, $R_{\max}$, is represented as

$$R_{\max} = \sum_{b=1}^{B} W \log_2\left(1 + \frac{\max_k (h_{k,b} / N_{k,b}) P}{BW}\right), \tag{1}$$

where $N_{k,b}$ is the noise plus inter-cell interference power density observed at the k-th user in the b-th frequency block. In the paper, we compare the cell-edge user throughput of the non-orthogonal access using superposition coding with the SIC and that of the orthogonal access when the total user throughput of these access is equal to or greater than $\alpha R_{\max}$ (α is a parameter, $0 \le \alpha \le 1$). The radio resources (frequency and power) are allocated so that the worst user throughput (minimum of the user throughput among multiple users in communication) is maximized while the total user throughput satisfies the target value for the given channel conditions for all users. The larger α means higher priority for total user throughput compared to the user fairness, and vice versa.

A. Orthogonal Access

When we use orthogonal access, the allocated frequencies for all users do not overlap. Let us assume that $\beta_{k,b}$ ($0 \le \beta_{k,b} \le 1$, $\Sigma_k\{\beta_{k,b}\} \le 1$) is the bandwidth allocation ratio to the k-th user at the b-th frequency block. Fixed transmission power density is also assumed. Fig. 1 illustrates an example of the radio resource allocation in orthogonal access. The user throughput of the k-th user, $R^{(o)}(k)$, is represented as

$$R^{(o)}(k) = \sum_{b=1}^{B} \beta_{k,b} W \log_2\left(1 + \frac{h_{k,b} P}{BWN_{k,b}}\right). \tag{2}$$

The problem to maximize the worst user throughput with the total user throughput constraint is written as

$$\begin{aligned} &\text{maximize } \min_k R^{(o)}(k) \\ &\text{subject to } \beta_{k,b} \ge 0, \forall k,b,\ \sum_{k=1}^{K} \beta_{k,b} \le 1, \forall b, \\ &\qquad \sum_{k=1}^{K} R^{(o)}(k) \ge \alpha R_{\max} \end{aligned} \tag{P1}$$

Problem (P1) is a convex optimization problem and is solved by the interior-point method [9] in the paper.

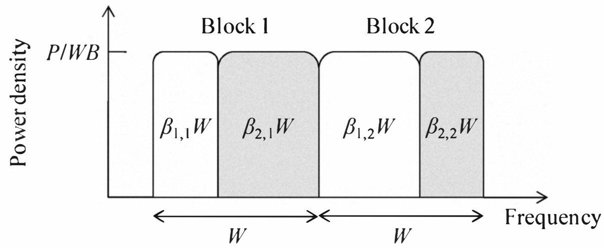


Figure 1. Transmission signal spectrum in orthogonal access.

B. Non-orthogonal Access with SIC

In the non-orthogonal access with a SIC, all users use overall transmission bandwidth BW and the transmission signals to the respective users are multiplexed using superposition coding. Fig. 2 shows a block diagram of the transmitter using superposition coding. Here, we assume two users. Each of the k-th user information bit sequences s_k is independently channel coded and modulated. The transmit signal is a simple summation of the coded modulation signals, x_k, of all users in the superposition coding. In the b-th frequency block, the SIC at the k-th user removes the inter-user interference from user i whose $h_{i,b}/N_{i,b}$ is lower than $h_{k,b}/N_{k,b}$ [2]. Thus, the SIC decoding order is in increasing order of the user channel gains. It is known that this order establishes the boundary of the capacity region in the single-input single-output (SISO) downlink [10]. Fig. 3 shows a block diagram of the receiver. Terms h_k and w_k are the path gain and noise plus inter-cell interference component for the k-th user, respectively (frequency block index b is omitted). The average power of w_k is N_k. We assume in Fig. 3 that the channel conditions for the second user are better than those for the first user, thus, $h_2/N_2 > h_1/N_1$. In this case, the SIC is not applicable to the first user, while the second user can increase the throughput by using the SIC as shown in Fig. 3. The k-th user throughput, $R^{(sic)}(k)$, is represented as

$$R^{(\mathrm{sic})}(k)=\sum_{b=1}^{B} W\log_2\left(1+\frac{h_{k,b}P_{k,b}}{\sum\limits_{i=1,h_{k,b}/N_{k,b}<h_{i,b}/N_{i,b}}^{K} h_{k,b}P_{i,b}+WN_{k,b}}\right), \quad (3)$$

where $P_{k,b}$ ($0 \le P_{k,b} \le P$) is the transmission power for the k-th user at the b-th frequency block. Since the fixed transmission power density is also assumed for non-orthogonal access with the SIC, $\Sigma_k\{P_{k,b}\}$ should be P/B for any b. Fig. 4 illustrates an example of the radio resource allocation in non-orthogonal access with the SIC.

The problem to maximize the worst user throughput with the total user throughput constraint is written as

$$\begin{aligned}&\text{maximize } \min_k R^{(\mathrm{sic})}(k)\\ &\text{subject to } P_{k,b}\ge 0, \forall k,b,\ \sum_{k=1}^{K} P_{k,b}=P/B, \forall b,\\ &\sum_{k=1}^{K} R^{(\mathrm{sic})}(k)\ge \alpha R_{\max}\end{aligned} \quad \text{(P2)}$$

Problem (P2) is not a convex optimization problem; therefore, the solution obtained using the interior-point method is dependent on the initial setting of parameters $P_{k,b}$. Considering (1), we use the following set of initial $P_{k,b}$ in the evaluation.

$$P_{k,b}=\begin{cases}P/B, & k=\arg\max\limits_{i}(h_{i,b}/N_{i,b})\\ 0, & \text{otherwise}\end{cases}. \quad (4)$$

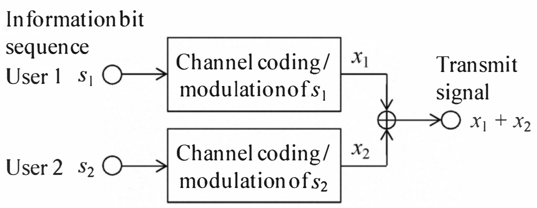


Figure 2. Signal processing at base station transmitter.

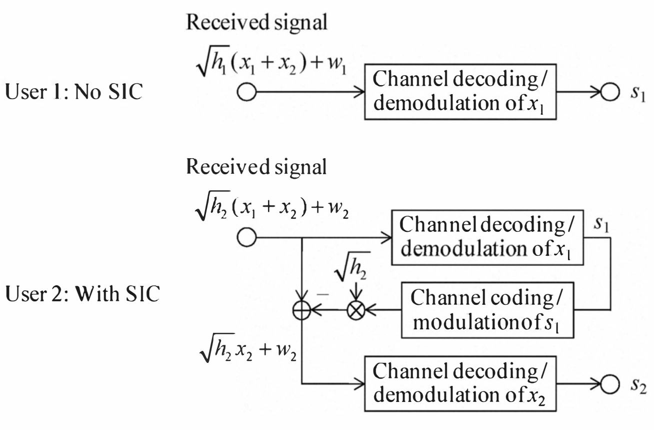


Figure 3. Signal processing at user terminal receiver.

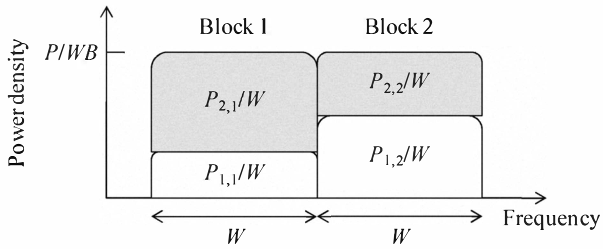


Figure 4. Transmission signal spectrum in non-orthogonal access with SIC.

III. Numerical Results

A. Simulation Parameters

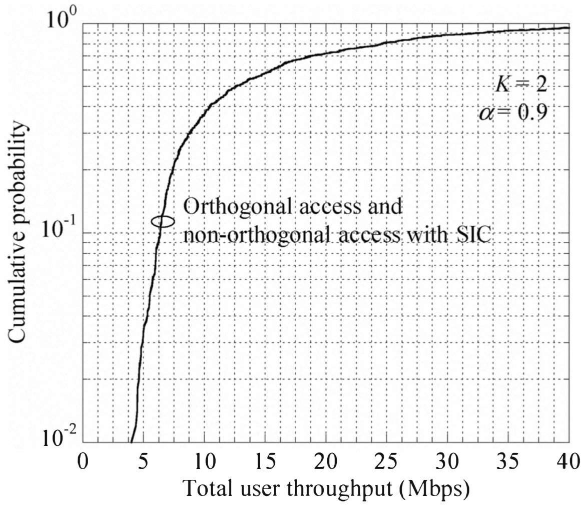
We evaluated the distribution of the user throughput. Table I gives the simulation parameters. A 19-cell model with a hexagonal grid, assuming universal frequency reuse is used. The cell radius is 500 m. The location of the user terminal in each cell is randomly assigned with a uniform distribution. W and B are set to 180 kHz [3] and 24, respectively (overall bandwidth is 4.32 MHz). The maximum transmission power at the base station is 43 dBm. 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 10 dB, and 6-path Rayleigh fading with the rms delay spread of 1 μs and the maximum Doppler frequency of 55.5 Hz. The receiver noise density of the user terminal is set to −169 dBm/Hz. Radio resource allocation is updated in 1-ms intervals. The user throughput averaged over 100 ms is measured.

TABLE I. Simulation Parameters

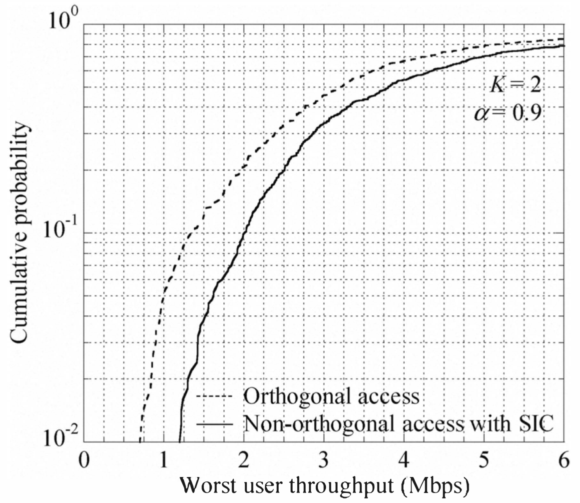
Cell layout	Hexagonal grid, 19 cell sites without sectorization
Cell radius	0.5 km
Base station transmission power, P	43 dBm
Distance-dependent path loss	$128.1 + 37.6 \log_{10}(r)$ dB, r: kilometers
Standard deviation of shadowing	10 dB
Instantaneous fading	Six-path Rayleigh rms delay spread = 1 μs f_D = 55.5 Hz
Number of transmitter antennas	1
Number of receiver antennas	1
Receiver noise density	-169 dBm/Hz
Overall transmission bandwidth, BW	4.32 MHz
RB bandwidth, W	180 kHz
Number of RBs, B	24
Number of user terminals per cell, K	2, 5, and 10
Throughput calculation	Based on Shannon formula
Averaging interval of throughput measurement	100 ms

B. Simulation Results

Figs. 5(a) and 5(b) show the cumulative distributions of the total user throughput and worst user throughput, respectively, for the case with K of 2. The non-orthogonal access with the SIC and orthogonal access are evaluated. The limiting factor of the total user throughput, α, is set to 0.9. Fig. 5(a) shows that non-orthogonal access with the SIC and orthogonal access achieve the same total user throughput. Meanwhile, Fig. 5(b) shows that non-orthogonal access with the SIC achieves a higher worst user throughput than that for orthogonal access. The performance gap is especially large in the low cumulative probability region. This means that non-orthogonal access with the SIC can increase the cell-edge user throughput while maintaining a high total user throughput compared to orthogonal access. This is due to the full-bandwidth usage of all users irrespective of the channel conditions and high-power allocation to the power-limited cell-edge users associated with the SIC process applied to the bandwidth-limited cell-interior users.



(a) Total user throughput



(b) Worst user throughput

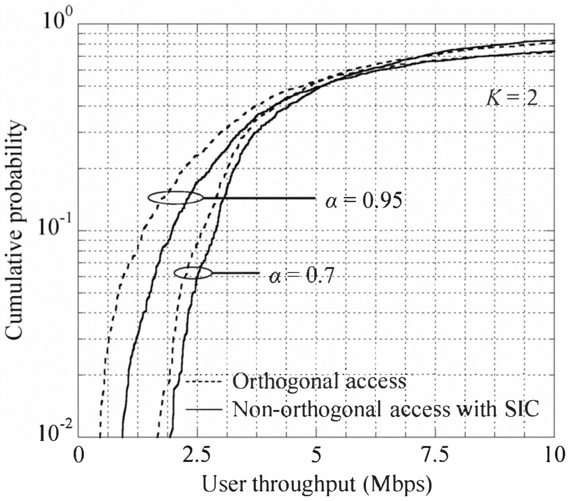
Figure 5. Cumulative distribution of total and worst user throughput ($K = 2$).

Figs. 6(a) and 6(b) show the cumulative distributions for the user throughput taking into account all the users in communication for K of 2 and 5, respectively. Parameter α of 0.95 and 0.7 are tested. Since the worst user throughput and total user throughput are in a tradeoff relationship, the user throughput at the point of low cumulative probability is increased as α is decreased. In the following, the user throughput value at the cumulative probability of 5% is denoted as the cell-edge user throughput. We can see that the cell-edge user throughput gain by using the non-orthogonal access with the SIC compared to the orthogonal access is especially significant when α is large. Therefore, the non-orthogonal access with the SIC is effective in achieving very high user fairness (cell-edge user throughput) and system efficiency (total user throughput) simultaneously. Comparing Fig. 6(a) and 6(b), we see that the performance enhancement by using non-orthogonal access with the SIC is increased as K increases.

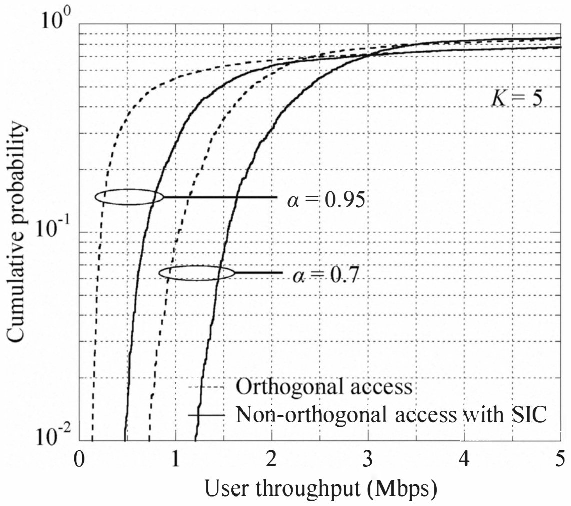
Figs. 7(a), 7(b), and 7(c) show the average and cell-edge user throughput as a function of α, for K = 2, 5, and 10, respectively. For comparison, the user throughput of the orthogonal access with the PF scheduler is also plotted (that is not a function of α). In the PF scheduler, the b-th frequency block is assigned to the user achieving the highest $h_{k,b}/E[h_{k,b}]$ among users. As α is decreased, the average user throughput decreases while the cell-edge user throughput increases. However, an excessively low α does not always contribute to an increase in the worst user throughput. For example, if the total user throughput requirement, $\Sigma_k\{R^{(o)}(k)\}$ or $\Sigma_k\{R^{(sic)}(k)\} \geq \alpha R_{max}$, is strictly inside the capacity region of a given channel, the optimal resource assignment achieves the same user throughput for all users while the total user throughput is still greater than αR_{max}. Therefore, the relationship between the average user throughput and α is not linear in the low α region. This is also the reason why the average user throughput for a given α in the low α region is not the same between the non-orthogonal access scheme with the SIC and the orthogonal access scheme. These two access schemes have different capacity regions for a given channel except for the case where all user channels (more specifically, $h_{k,b}/N_{k,b}$) are completely identical.

We see that the cell-edge user throughput gain increases by using the non-orthogonal access scheme with the SIC compared to the orthogonal access scheme especially when α is large. Furthermore, the improvement in the cell-edge user throughput by using non-orthogonal access with the SIC is even enhanced as K increases. This is because orthogonal access reduces the bandwidth allocation to the users especially under poor channel conditions as K increases, while non-orthogonal access with the SIC allocates the full bandwidth to all users irrespective of the channel conditions and K. When K is 2, the cell-edge user throughput of the non-orthogonal access with the SIC is approximately 1.1 and 1.8 times larger than that for orthogonal access for α of 0.7 and 0.95, respectively. When K is 10, the cell-edge user throughput is increased to approximately 1.9 and 4.2 times for α of 0.7 and 0.95, respectively. Therefore, the enhancement of the user fairness by using non-orthogonal access with the SIC is effective especially when a large number of users is accommodated in the system.

Finally, when we compare the non-orthogonal access with the SIC and orthogonal access with the PF scheduler, the non-orthogonal access with the SIC achieves approximately 1.5, 2.5, and 3.8 times higher cell-edge user throughput than orthogonal access with the PF scheduler for K of 2, 5, and 10, respectively, while achieving the same average user throughput. These results indicate the effectiveness of applying non-orthogonal access with the SIC to the typical regime of the tradeoff between user fairness (cell-edge user throughput) and system efficiency (total user throughput) assumed in the current cellular systems.

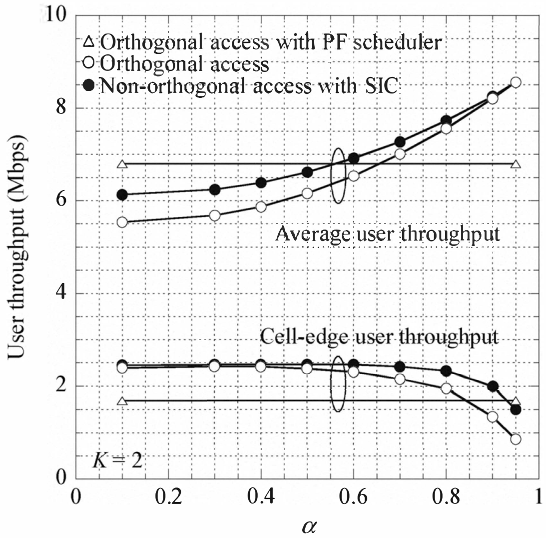


(a) $K = 2$

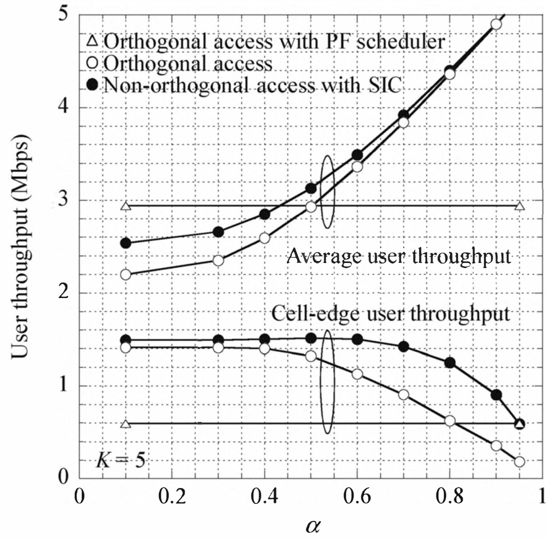


(b) $K = 5$

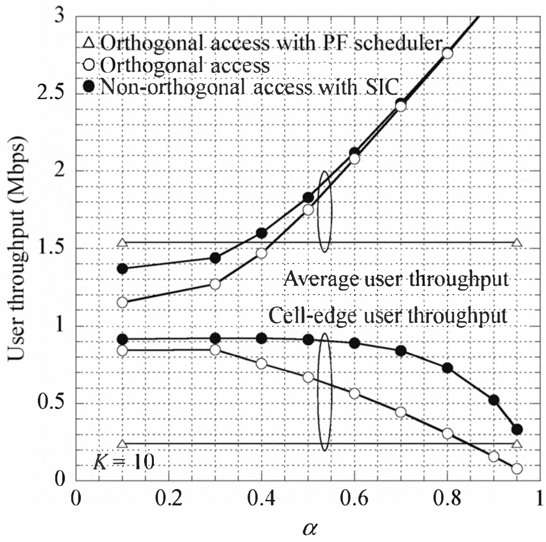
Figure 6. Cumulative distribution of user throughput.



(a) $K = 2$



(b) $K = 5$



(c) $K = 10$

Figure 7. Average and cell-edge user throughput as a function of α.

IV. CONCLUSION

This paper investigated the enhancement of the cell-edge user throughput by using non-orthogonal access with the SIC in the cellular downlink compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems. Since both the total user throughput and cell-edge user throughput are important in a real system, we compared the cell-edge user throughput while subject to the same total user throughput. The optimum resource allocation in terms of bandwidth and transmission power for each user was assumed for the respective access schemes based on the instantaneous channel conditions. The evaluation results showed that non-orthogonal access with the SIC can significantly enhance the cell-edge user throughput (thus user fairness) compared to orthogonal access while achieving the same total user throughput in the context of the cellular downlink. Performance enhancement is expected to be increased as the number of communicating users increases. Furthermore, when comparing non-orthogonal access with the SIC and orthogonal access with the PF scheduler, we found that non-orthogonal access with the SIC is effective in improving the user fairness even when the requirement for the total user throughput is alleviated. Based on these results, we believe that non-orthogonal access with an advanced transceiver such as the SIC is a promising wireless access scheme for the systems beyond IMT-Advanced.

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