Performance of Non-orthogonal Access with SIC in Cellular Downlink Using Proportional Fair-Based Resource Allocation

Nagisa Otao†, 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—**This paper investigates the system-level throughput of non-orthogonal access with a successive interference canceller (SIC) in the cellular downlink assuming proportional fair (PF)-based radio resource (bandwidth and transmission power) allocation. The purpose of this study is to examine the possibility of applying non-orthogonal access with a SIC to the systems beyond the 4G (thus IMT-Advanced) cellular system. Both the total and cell-edge average user throughput are important in a real system. PF-based scheduling is known to achieve a good tradeoff by maximizing the product of the average user throughput among users within a cell. In non-orthogonal access with a SIC, the scheduler allocates the same frequency to multiple users, which necessitates multiuser scheduling. To achieve a better tradeoff between the total and cell-edge average user throughput, we propose and compare three power allocation strategies among users, which are jointly implemented with multiuser scheduling. Extensive simulation results show that non-orthogonal access with a SIC with a moderate number of non-orthogonally multiplexed users significantly enhances the system-level throughput performance compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems.**

I. INTRODUCTION

In 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 3.9 and 4th generation mobile communication systems such as LTE [1] and LTE-Advanced [2, 3]. Orthogonal access was a reasonable choice for achieving good system-level throughput performance in packet-domain services using channel-aware time- and frequency-domain scheduling with simple single-user detection.

However, for systems beyond 4G, further enhancement of the system throughput and user fairness is required considering the recent exponential increase in the volume of mobile traffic and the needs for enhanced delay-sensitive high-volume services such as video streaming and cloud computing. To accommodate such requirements, 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) [4], which is different from the 3rd generation mobile communication system. An attractive feature of non-orthogonal access with advanced transmission/reception techniques is to improve the tradeoff between the total user throughput and user fairness with regard to the achievable user throughput of the respective user. 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 user throughput [5]. In a real system, both the total user throughput and cell-edge user throughput are important performance metrics, e.g., in [1] and [2]. Although there are several studies that compare orthogonal and non-orthogonal access in the context of a cellular system [6-9], most of these studies consider only one of the two metrics. This paper differs from previous papers in that we evaluate the cell-edge user throughput and total user throughput simultaneously.

It is known that proportional fair (PF)-based scheduling [10, 11] achieves a good tradeoff between the total and cell-edge average user throughput by maximizing the product of the average user throughput among users within a cell. The PF scheduler has been widely used in the 3G and 3.9G orthogonal access systems. Therefore, we consider the application of the PF scheduler to non-orthogonal access with a SIC. In non-orthogonal access with a SIC, the scheduler allocates the same frequency to multiple users, which necessitates multiuser scheduling. To achieve a better tradeoff between the total average user throughput and cell-edge average user throughput, we propose three power allocation strategies among users, which are jointly conducted with multiuser scheduling, and compare them.

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

II. SYSTEM MODEL

We assume orthogonal frequency division multiplexing (OFDM) signaling with a cyclic prefix, although we also 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. We assume universal frequency reuse among cells.

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 $N_r = 2$. The number of users per cell is K. There are B frequency blocks and the bandwidth of a frequency block is W.

We assume that the multiuser scheduler schedules a set of users, $\mathcal{S}_b = \{i_b(1), i_b(2), ..., i_b(m_b)\}$, to a frequency block, b ($1 \leq b \leq B$). Term $i_b(l)$ indicates the l-th ($1 \leq l \leq m_b$) user index scheduled at frequency block b, and m_b denotes the number of scheduled users at frequency block b. In this section, the time index, t, is omitted for simplicity. At the base station transmitter, each $i_b(l)$-th user information bit sequence is independently channel coded and modulated. The 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

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

where $E[|s_b(i_b(l))|^2] = 1$ and $p_b(i_b(l))$ is the allocated transmission power for user $i_b(l)$ at frequency block b. The N_r-dimensional received signal vector of user $i_b(l)$ at a certain subcarrier of frequency block b, $\mathbf{y}_b(i_b(l))$, is represented as

$$\mathbf{y}_b(i_b(l)) = \mathbf{h}_b(i_b(l)) x_b + \mathbf{w}_b(i_b(l)), \tag{2}$$

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. Since we assume that the receiver treats inter-cell interference as white noise, the receiver performs maximum ratio combining (MRC) on $\mathbf{y}_b(i_b(l))$ as

$$\begin{aligned} \tilde{y}_b(i_b(l)) &= \mathbf{h}_b^H(i_b(l)) \mathbf{y}_b(i_b(l)) / \| \mathbf{h}_b \| \\ &= \| \mathbf{h}_b(i_b(l)) \| x_b + \mathbf{h}_b^H(i_b(l)) \mathbf{w}_b(i_b(l)) / \| \mathbf{h}_b \|, \\ &= \sqrt{g_b(i_b(l))} x_b + z_b(i_b(l)) \end{aligned} \tag{3}$$

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 $n_b(i_b(l)) = E[|z_b(i_b(l))|^2]$.

The total transmission power per subcarrier of the base station is assumed to be P, which is constant for all frequency blocks. One merit of a 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 to achieve the optimum radio resource allocation. A drawback may be the degraded achievable throughput because the water-filling principle is not utilized. However, since the throughput degradation on average is small in a typical cellular scenario with a sufficiently large number of users, we assume fixed transmission power density in the paper. Therefore, the transmission power allocation constraint is represented as

$$\sum_{l=1}^{m_b} p_b(i_b(l)) = P \cdot \tag{4}$$

In the paper, we assume that inter-user interference cancellation is performed at the receiver. Thus the SIC is implemented, since DPC is difficult to implement and sensitive to the error in the channel state information feedback.

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

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

III. MULTIUSER SCHEDULING

In non-orthogonal access with a SIC, the scheduler can allocate a frequency block to more than one user simultaneously. The scheduling policy significantly 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 [10, 11] is known to achieve a good tradeoff between them by maximizing the product of the average user throughput among users within a cell. In [12], the multiuser scheduling version of the PF scheduler is presented. In this paper, the method in [12] is extended to the case with multiple frequency blocks and applied to non-orthogonal access with a SIC.

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

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

where t denotes the time index representing a subframe index. Parameter t_c defines the time horizon for throughput averaging. We assume t_c of 100 with the subframe length of 1 ms in the following evaluation (thus 100-ms average 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 at 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.

$$f_b(\mathcal{S}) = \prod_{k \in \mathcal{S}} \left(1 + \frac{R_b(k \mid \mathcal{S};t)}{(t_c - 1) T(k;t)} \right). \tag{7}$$

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

$f_b(\mathcal{S})$ is the scheduling metric for user set $\mathcal{S}$, and user set $\mathcal{S}$ that maximizes the scheduling metric is selected.

The remaining problem is the transmission power allocation to the scheduled users. In non-orthogonal access with a SIC, the power allocation to certain users affects the achievable throughput of not only that user but also other users due to inter-user interference. Therefore, transmission power allocation and multiuser scheduling are related to each other. Our approach is that for each candidate set of users, $\mathcal{S}$, we perform power allocation first and then calculate the scheduling metric, $f_b(\mathcal{S})$. We consider the optimal power allocation method for maximizing (8) and two suboptimal methods, which are presented in the following section.

IV. Transmission Power Allocation

A. Optimal Method

When $t_c >> 1$, which is valid in the paper where $t_c = 100$, (7) can be approximated as

$$f_b(\mathcal{S}) \approx \sum_{k\in \mathcal{S}} \frac{1}{T(k;t)} R_b(k \mid \mathcal{S};t) \cdot \tag{9}$$

Equation (9) is a weighted sum of instantaneous user throughput $R_b(k \mid \mathcal{S};\, t)$ where the weighting factor for user k is the inverse of its average user throughput, $T(k;\, t)$. Therefore, for given candidate scheduling policy $\mathcal{S}$, the metric can be maximized by the power allocation that maximizes the weighted sum of the instantaneous user throughput. In [13], the iterative water-filling power allocation algorithm achieving this maximization is presented. The optimal method applies this algorithm. For the problem at hand, the optimal power allocation algorithm can be described as follows.

Step 1) Initial setting

- ✓ Users in set $\mathcal{S}$ are sorted in order of the increasing average user throughput, $T(k;\, t)$. The k-th sorted user index is denoted as $\pi(k)$.
- ✓ $\Delta(k) := 1/T(\pi(k);\, t) - 1/T(\pi(k+1);\, t)$, where $1/T(\pi(|\mathcal{S}|+1);\, t)$ is assumed to be zero.
- ✓ $q_b^{(0)}(\pi(k)) := 0\ \forall \pi(k) \in \mathcal{S}$. Term $q_b(\pi(k))$ represents the transmission power for user $\pi(k)$ in the dual uplink multiple access channel (MAC).
- ✓ Iteration index n is set to 1.

Step 2) Water-filling step for updating power calculation

- ✓ $$\beta^{(n)}(\pi(k),l) := \frac{g_b(\pi(k))/n_b(\pi(k))}{1+\sum_{i=1,i\neq k}^{l} g_b(\pi(i))q_b^{(n-1)}(\pi(i))/n_b(\pi(i))}$$
- ✓ Updating power $\gamma_b^{(n)}(\pi(k))$ is determined so that

$$\sum_{l=k}^{|\mathcal{S}|} \frac{\Delta_l}{\gamma_b^{(n)}(\pi(k)) + 1/\beta^{(n)}(\pi(k),l)} = \mu\ \forall k,$$

$$\sum_{\pi(k)\in \mathcal{S}} \gamma_b^{(n)}(\pi(k)) = P$$

Step 3) Updating step

- ✓ $$q_b^{(n)}(\pi(k)) := (1/|\mathcal{S}|)\gamma_b^{(n)}(\pi(k)) + (1-1/|\mathcal{S}|)q_b^{(n-1)}(\pi(k))$$

Step 4) $n := n+1$. Return to Step 2 for sufficient convergence.

After convergence, the set of $\{q_b^{(n)}(\pi(k))\}$ for the dual MAC is converted to power allocation $\{p_b(\pi(k))\}$ in the downlink based on the uplink-downlink duality presented, e.g., in [14]. The optimal power allocation with multiuser scheduling using (8) maximizes the product of the average user throughput.

B. Suboptimal Methods

Since the optimal power allocation is computationally complex and feedback of the determined allocated power to the respective users is needed, we consider the following two simple but suboptimal power allocation methods.

The first method is a fixed (channel-independent) power allocation. We assume that the users in set $\mathcal{S}$ are sorted in order of the decreasing normalized channel gain, $g_b(k)/z_b(k)$. The k-th sorted user index is denoted as $\pi(k)$. The transmission power of user $\pi(k)$ is set to

$$p_b(\pi(k)) = \alpha_{fix}\, p_b(\pi(k+1)), \tag{10}$$

with a sum power constraint. Parameter α_{fix} ($0 < \alpha_{fix} \leq 1$) controls the system efficiency and user fairness. As α_{fix} increases, the system tends to allocate more power to the users experiencing good channel conditions. Since the value of α_{fix} is fixed, the users can know its allocated power from the information pertaining to the number of scheduled users and user order, which is needed anyway for SIC operation.

The second method is fractional power allocation motivated by the fractional transmission power control used in the LTE uplink [1]. In this method, power control compensates for a part of the variation in the channel conditions among users. The transmission power of user k is determined as

$$p_b(k) = \frac{P}{\sum_{j\in \mathcal{S}} \left(g_b(j)/n_b(j)\right)^{-\alpha_{ftpc}}} \left(\frac{g_b(k)}{n_b(k)}\right)^{-\alpha_{ftpc}}, \tag{11}$$

where α_{ftpc} ($0 \leq \alpha_{ftpc} \leq 1$) is the decay factor. When $\alpha_{ftpc} = 0$, equal power allocation is achieved. As α_{ftpc} increases, more power is allocated to the user with a low $g_b(k)/z_b(k)$ value. The fractional power allocation is simpler than the optimal one, but the respective users must be made aware of the allocated power by explicit control signaling, which differentiates this allocation from the fixed power allocation.

V. Simulation Results

A. Simulation Parameters

Here we evaluate the distribution of the user throughput in a multi-cell downlink. Table I gives the simulation parameters. A 19-cell model with a hexagonal grid assuming universal frequency reuse is used. The inter-site distance is 500 m. The number of users per cell, K, is set to 30. The locations of the user terminals in each cell are randomly assigned with a uniform distribution. The values for W and B are set to 180 kHz [1] and 24, respectively (overall transmission bandwidth is 4.32 MHz). The transmission power at the base station is 40 dBm. We take into account the distance-dependent path loss with the decay factor of 3.76, lognormal shadowing with the standard deviation of 8 dB and 0.5-correlation among sites, 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 −169 dBm/Hz. The radio resource allocation is updated every 1 ms. 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, N_{max}, is parameterized from 1 to 4. In the scheduling, all possible user sets $\mathcal{S}$, where $|\mathcal{S}| \leq N_{max}$, are examined and the user set achieving the highest scheduling metric is selected. The N_{max} of one corresponds to the orthogonal access based on OFDMA. In the following, we simply denote the average user throughput of 100 ms as the user throughput to avoid confusion with the average of the throughput among users within a cell.

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
Lognormal 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. 1 shows the cumulative distributions of the user throughput. The N_{max} values of one, two, and three are shown. The optimum power allocation is assumed. The figure clearly shows that non-orthogonal access with a SIC (thus $N_{max} > 1$) using PF-based resource allocation achieves better throughput than orthogonal access for the entire region of the cumulative distribution. This is because the user throughput of the orthogonal access is severely limited by the orthogonal bandwidth allocation, which reduces the bandwidth for the respective users. Non-orthogonal access with a SIC allows for wider bandwidth usage of all users irrespective of the channel conditions. Allocating high power to the power-limited cell-edge users associated with the SIC process, which is applied to the bandwidth-limited cell-interior users, enhances the throughput of the users under a wide range of channel conditions. The impact of the transmission bandwidth limitation on orthogonal access is especially clear in the high cumulative distribution probability region, where the users are under bandwidth-limited conditions. The gain by further increasing N_{max} from two to three is relatively small. This indicates that it is sufficient to multiplex non-orthogonally a moderate number of users to obtain the most from the potential gain using non-orthogonal access with a SIC. In the following, the user throughput value at the cumulative probability of 5% is denoted as the cell-edge user throughput [1, 2].

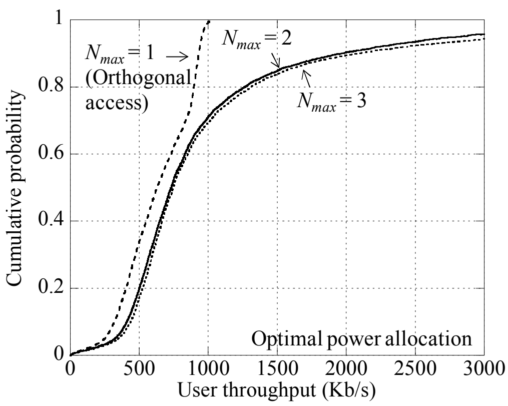

Figure 1. Cumulative distribution of user throughput.

Fig. 2 shows the geometric mean user throughput for a fixed transmission power allocation as a function of α_{fix}. Here, the geometric mean user throughput is used since it is a good system performance measure that simultaneously takes into account the system efficiency and user fairness. In the figure, N_{max} is parameterized from one to four. The performance with optimal transmission power allocation is also plotted. In the fixed transmission power allocation, as α_{fix} increases from zero, the system tends to allocate more power to the users experiencing good channel conditions, which contributes to the system efficiency mainly by increasing the throughput of the users near the base station. However, since the cell-edge user throughput tends to decrease at the same time, there is an optimum α_{fix} value. From the viewpoint of the geometric mean user throughput, the optimum α_{fix} value is approximately 0.1 under the simulation assumptions. Even with a near optimum α_{fix}, the geometric mean user throughput of the fixed transmission power allocation is lower than that for the optimum power allocation since the optimum power allocation maximizes the geometric mean user throughput along with the PF-based multiuser scheduling. However, the performance gap tends to decrease as N_{max} increases. This may be because the PF-based multiuser scheduling for a given power allocation can mitigate the suboptimal power allocation as N_{max} is increased. We can clearly see that by increasing N_{max} from one, the geometric mean user throughput is significantly increased.

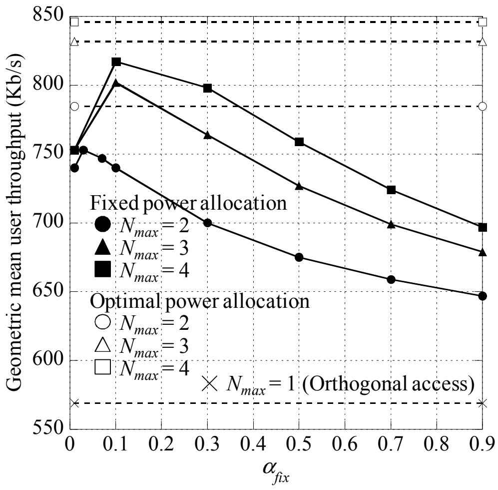

Figure 2. Geometric mean user throughput for fixed transmission power allocation as a function of α_{fix}.

Fig. 3 shows the geometric mean user throughput for fractional transmission power allocation as a function of α_{ftpc}. In the fractional transmission power allocation, as α_{ftpc} increases, more power is allocated to the users experiencing worse channel conditions. Similar to the reason in the fixed power allocation, there is an optimal α_{ftpc} value to achieve a tradeoff between the system efficiency and user fairness. For the optimal α_{ftpc} value, the geometric mean user throughput of the fractional transmission power allocation is higher than that with the fixed power allocation since the fractional transmission power allocation takes into account the channel conditions of the respective non-orthogonally multiplexed users. However, the performance gain is not so significant. Therefore, if the system places priority on reducing the signaling overhead for transmission power control, the fixed power allocation approach may be appropriate.

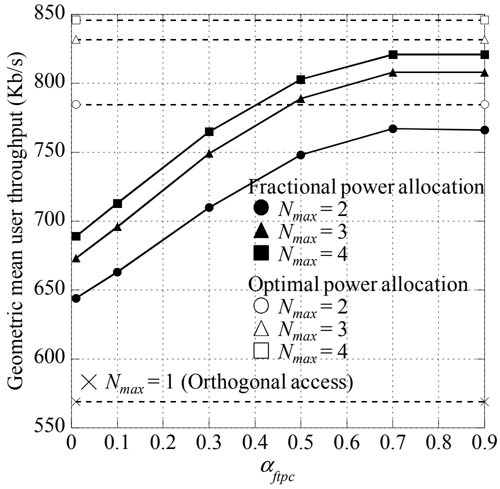

Figure 3. Geometric mean user throughput for fractional transmission power allocation as a function of α_{ftpc}.

Fig. 4 shows the arithmetic mean and cell-edge user throughput as a function of N_{max}. The arithmetic mean and cell-edge user throughput is the basic performance measure in LTE and LTE-advanced [1, 2]. For the suboptimal power allocation strategies, the α_{fix} or α_{ftpc} value that maximizes the geometric mean user throughput is assumed. We can see that non-orthogonal access with a SIC with PF-based resource allocation increases the arithmetic mean and cell-edge user throughput simultaneously compared to orthogonal access (N_{max} = 1). When N_{max} is 4, non-orthogonal access with a SIC simultaneously achieves approximately 2.0 and 1.4 fold gains in the arithmetic mean and cell-edge user throughput, respectively. Among the three power allocation strategies, the optimal power allocation achieves the best performance. However, the performance degradation with suboptimal power allocation is not significant. Even with the fixed power allocation, which is channel independent, the loss in the arithmetic mean and cell-edge user throughput compared to the case with the optimal power allocation is within 5% for the N_{max} of 4.

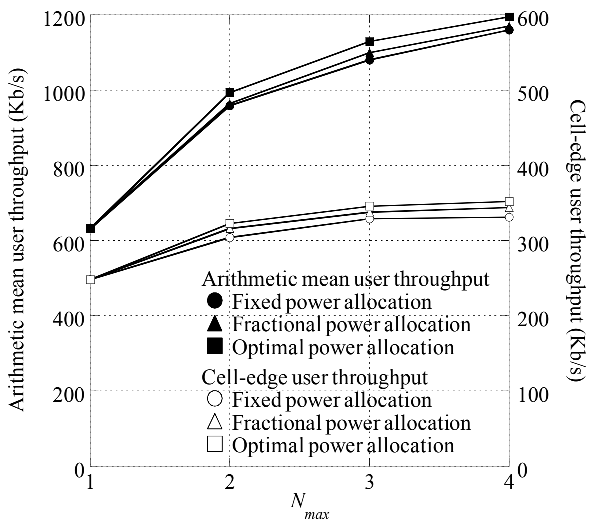

Figure 4. Arithmetic mean and cell-edge user throughput as a function of N_{max}.

VI. Conclusion

This paper investigated the system-level throughput performance of non-orthogonal access with a SIC in the cellular downlink. We employed PF-based radio resource (bandwidth and transmission power) allocation to enhance both the system efficiency and cell-edge user experience in a realistic manner. The simulation results indicate that non-orthogonal access with a SIC with a moderate number of non-orthogonally multiplexed users significantly enhances the system-level throughput performance compared to orthogonal access, which is widely used in 3.9 and 4G mobile communication systems. Although the optimal power allocation achieves the best system-level throughput, a suboptimal allocation such as the fixed channel-independent power allocation may be attractive considering the signaling overhead by introducing non-orthogonal access and computational complexity in the resource allocation. Based on these results, we believe that non-orthogonal access with an advanced transceiver such as a SIC is a promising wireless access scheme for the systems beyond IMT-Advanced. To verify the effectiveness of non-orthogonal access with a SIC, a performance evaluation assuming a realistic channel code and QAM data modulation and residual interference in the SIC process is needed. The design of realistic control signaling is also an important issue. These issues are left for future study.

References

[1] 3GPP TS36.300, Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description.

[2] 3GPP TR36.913 (V8.0.0), "3GPP; TSG RAN; Requirements for further advancements for E-UTRA (LTE-Advanced)," June 2008.

[3] 3GPP TR36.814 (V9.0.0), "Further advancements for E-UTRA physical layer aspects," Mar. 2010.

[4] G. Caire and S. Shamai, "On the achievable throughput of a multi-antenna Gaussian broadcast channel," IEEE Trans. Inf. Theory, vol. 49, no. 7, pp. 1692-1706, July 2003.

[5] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*. Cambridge University Press, Cambridge, U.K., 2005.

[6] H. Jin, R. Laroia, and T. Richardson, "Superposition by position," in Proc. 2006 IEEE Information Theory Workshop, Punta del Este, Uruguay, Mar. 2006.

[7] P. Wang, J. Xiao, and L. Ping, "Comparison of orthogonal and non-orthogonal approaches to future wireless cellular systems," IEEE Vehicular Technology magazine, vol. 1, no. 3, pp. 4-11, Sept. 2006.

[8] J. Schaepperle and A. Ruegg, "Enhancement of throughput and fairness in 4G wireless access system by non-orthogonal signaling," Bell Labs Technical Journal, vol. 13, no. 4, pp. 59-77, Winter 2009.

[9] J. Schaepperle, "Throughput of a wireless cell using superposition based multiple-access with optimized scheduling," in Proc. IEEE PIMRC2010, Istanbul, Turkey, Sept. 2010.

[10] F. Kelly, "Charging and rate control for elastic traffic," European Transactions on Telecommunications, vol. 8, pp. 33-37, 1997.

[11] A. Jalali, R. Padovani, and R. Pankaj, "Data throughput of CDMA-HDR a high efficiency-high data rate personal communication wireless system," in Proc. IEEE VTC2000-Spring, May 2000.

[12] M. Kountouris and D. Gesbert, "Memory-based opportunistic multi-user beamforming," in Proc. IEEE Int. Symp. Information Theory (ISIT), Adelaide, Australia, Sept. 2005.

[13] M. Kobayashi and G. Caire, "An iterative water-filling algorithm for maximum weighted sum-rate of Gaussian MIMO-BC," IEEE J. Sel. Areas. Commun., vol. 24, no. 8, pp. 1640-1646, Aug. 2006.

[14] P. Viswanath and D. N. C. Tse, "Sum capacity of the vector Gaussian broadcast channel and uplink-downlink duality," IEEE Trans. Inf. Theory, vol. 49, no. 8, pp. 1912-1921, Aug. 2003.