Enhancing User Fairness in NOMA for Downlink CoMP Networks

Chia-An Ku and Char-Dir Chung
Graduate Institute of Communication Engineering, National Taiwan University
Email: r05942032@ntu.edu.tw; cdchung@ntu.edu.tw

Abstract —Non-orthogonal multiple access (NOMA) can be effectively integrated in downlink coordinated multipoint (CoMP) mobile networks to enhance transmission performance, particularly at cell boundaries. In this paper, the user fairness in joint-transmission NOMA (JT-NOMA) is investigated. To enhance the user fairness, the α-fairness JT-NOMA scheme and the product-rate-based JT-NOMA scheme are proposed. It is shown that the product-rate-based JT-NOMA scheme can provide comparable sum-rate performance to conventional JT-NOMA scheme while yielding better user fairness, and that the α-fairness JT-NOMA scheme can provide flexible user fairness by adjusting the factor α.

Index Terms—Non-orthogonal multiple access, coordinated multipoint, sum rate maximization, product rate maximization, user fairness.

I. Introduction

The cell-edge users of cellular networks face poor service due to weak channel condition and strong intercell interference. To overcome the problem, coordinated multi-point (CoMP) with joint transmission (JT) has been recently proposed to increase the system throughput by coordinating neighboring base stations (BSs) to serve User Equipments (UEs) at cell edges jointly [1]. However, in CoMP transmission, BSs need to allocate the dedicated channel to each individual UE and this channel cannot be shared with the other UEs simultaneously if orthogonal multiple access (OMA) is adopted. As a result, the spectral effectiveness of CoMP networks degrades as the number of UEs increases. This arouses the application of non-orthogonal multiple access (NOMA) in [2] to enhance cell-edge transmission performance without decreasing spectral effectiveness in CoMP.

In NOMA systems, BSs transmit signals at the same time, frequency and code but with different power levels. Superposition Coding (SC) and Successive Interference Cancellation (SIC) are used at transmitters and receivers respectively [3]. UEs with good channel conditions are called strong users and the others are called weak users. Weak users are allocated with more power whereas strong users are allocated with less power for the purpose of user fairness. Weak users decode their own messages by treating the strong users' messages as noise. On the other hand, strong users implement SIC technique to decode their own messages by removing the weak users' messages from the received signal [3].

For single-cell NOMA systems, the user fairness has been investigated in [4] and [5], and sum rate maximization well studied in [6]. NOMA has been proposed in [7] for use in the downlink coordinated two-point system using Alamouti code and extended in [8] to downlink CoMP. Although the joint-transmission NOMA (JT-NOMA) scheme has been proposed and shown in [8], it disregards user fairness and achieves high sum rate by providing strong users with much more throughput than weak users when maximizing the achievable sum rate. Low throughput may prohibit individual weak users from transmission. To alleviate the problem, the α-fairness JT-NOMA scheme and the product-rate-based JT-NOMA (PR-based JT-NOMA) scheme are proposed in this paper to enhance user fairness in downlink CoMP networks while providing as high sum rate as possible. Specifically, sum rate maximization problems are reformulated either with an additional fairness constraint in α-fairness JT-NOMA or by a new fairness-enabling object function in PR-based JT-NOMA to provide sum rate performance comparable to conventional JT-NOMA while yielding better user fairness. The α-fairness JT-NOMA scheme is proposed in Section II and the PR-based JT-NOMA scheme in Section III. Performance results in Section IV show that the proposed α-fairness JT-NOMA and PR-based JT-NOMA outperform conventional JT-NOMA in terms of user fairness in all signal-to-noise ratio (SNR) regions. Besides, PR-based JT-NOMA provides better user fairness than α-fairness JT-NOMA when there are more than two NOMA users in downlink CoMP.

II. Sum-Rate-Based JT-NOMA

A. Conventional JT-NOMA

In this paper, we consider a downlink NOMA system for CoMP networks. There are B BSs and U UEs in the network, as illustrated in Fig. 1. For convenience, we

Manuscript received July 21, 2018; revised March 2, 2019.
This work was supported by the Ministry of Science and Technology of ROC under Grant MOST 106-2221-E-002-026-MY3.
Corresponding author email: cdchung@ntu.edu.tw
doi:10.12720/jcm.14.4.312-317

denote $\mathcal{B} \triangleq \{1,2,...,B\}$ and $\mathcal{U} \triangleq \{1,2,...,U\}$ respectively as the sets of BS indices and UE indices, P as the total transmission power at all BSs, s_u as the message to be sent to UE u with $u \in \mathcal{U}$, where the power of s_u is normalized to one (i.e., $E\{|s_u|^2\}=1$), R_u as the achievable data rate of detecting s_u at UE u, $h_{b,u}$ as the channel response from BS b to UE u, and n_u as the additive white Gaussian noise with mean zero and variance σ^2 at UE u. It is assumed that all noises n_u's are independent and all channel responses $h_{b,u}$'s are perfectly known to all BSs and UEs. Based on known channel responses, NOMA schemes are targeted to achieve high system throughput $R_{\text{sum}} = \sum_{u\in\mathcal{U}} R_u$ as follows.

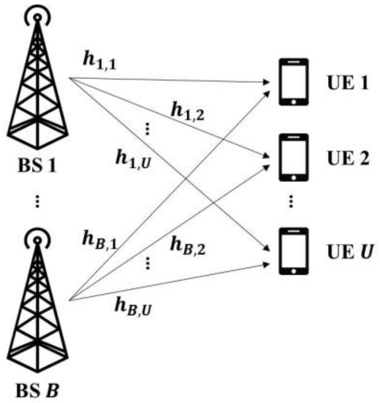

Fig. 1. NOMA model in a downlink CoMP network

In conventional JT-NOMA scheme [8], every BS is allocated with the same transmit power $a_u P$ to UE u for $u \in \mathcal{U}$, where a_u represents the proportion of total power allocated to transmit s_u in all BSs with $\sum_{u\in\mathcal{U}} a_u = 1/B$, and broadcasts the same total message $\sum_{u\in\mathcal{U}} \sqrt{a_u P} s_u$ to all users. The received signal observed at UE u is thus given by $r_u = \hat{h}_u \sum_{i\in\mathcal{U}} \sqrt{a_i P} s_i + n_u$ where $\hat{h}_u \triangleq \sum_{b\in\mathcal{B}} h_{b,u}$ represents the equivalent channel observed by UE u. Without loss of generality, it is assumed that $|\hat{h}_1|^2 \le |\hat{h}_2|^2 \le \cdots \le |\hat{h}_U|^2$. According to the SC principle, power allocation coefficients a_u's are constrained in the order $a_1 \ge a_2 \ge \cdots \ge a_U$, and the desirable message s_u can be reliably detected by the receiver at UE u respectively for $u \in U$, based on the SIC technique [2]. Specifically, s_i can be reliably detected by the receiver at UE u for $i < u$ because $R_{u\to i} \ge R_i$ is guaranteed, where $R_{u\to i}$ denotes the achievable data rate of detecting s_i at UE u, and all s_i for $i < u$ can be thus removed successively before detecting s_u by the SIC receiver at UE u. Therefore, the achievable data rate of detecting s_u at UE u is given by

$$R_u = \begin{cases} \log_2\left(1+\dfrac{|\hat{h}_u|^2 a_u P}{|\hat{h}_u|^2 P \sum_{i=u+1}^{U} a_i + \sigma^2}\right), & \text{if } 1 \le u < U \\ \log_2\left(1+\dfrac{|\hat{h}_u|^2 a_u P}{\sigma^2}\right), & \text{if } u = U \end{cases} \tag{1}$$

The system throughput of U UEs in the JT-NOMA system is given by $R_{\text{sum}} = \sum_{u\in\mathcal{U}} R_u$. Therefore, the throughput maximization problem can be formulated as

$$\begin{aligned} &\text{maximize} \quad R_{\text{sum}} \\ &\text{Subject to} \quad \sum_{u=1}^{U} a_u = \frac{1}{B} \\ &\qquad\qquad a_1 \ge \cdots \ge a_U \ge 0. \end{aligned} \tag{2}$$

B. α-fairness JT-NOMA

In the conventional JT-NOMA scheme, the achievable data rate of UE U is much higher than the other UEs and this causes a fairness problem. Straightforwardly, this problem can be resolved by adding a fairness constraint characterized by fairness factor α, as in [9] where quality of service (QoS) constraints for all UEs are applied to enhance the user fairness in single-cell downlink NOMA systems. Specifically, the QoS constraints are defined here as $R_u \ge R_{\text{sum}}\alpha / U$ for $u \in \mathcal{U}$ where α denotes the proportion of the equally appropriated rate to each user (i.e., R_{sum}/U) with $0 \le \alpha \le 1$. Under these QoS constraints, each UE's achievable data rate cannot be smaller than the minimum guaranteed data rate $R_{\text{sum}}\alpha / U$. Therefore, the throughput maximization problem in the α-fairness JT-NOMA scheme can be formulated as in (3).

$$\begin{aligned} &\text{maximize} \quad R_{\text{sum}} \\ &\text{Subject to} \quad \sum_{u=1}^{U} a_u = \frac{1}{B} \\ &\qquad\qquad a_1 \ge \cdots \ge a_U \ge 0 \\ &\qquad\qquad R_u \ge R_{\text{sum}}\alpha / U, u \in \mathcal{U}. \end{aligned} \tag{3}$$

When $\alpha = 0$, the maximization problem reduces to the conventional JT-NOMA without fairness. The α-fairness JT-NOMA scheme increases its fairness when α is increased and provides the same data rate for all UEs when $\alpha = 1$. A direct choice to enhance fairness seems to set α as close to one as possible. Unfortunately, the solution of the maximization problem in (3) does not always exist for large values in the range $0 \le \alpha \le 1$, especially when α approaches to 1. By simulation, it can be observed that the maximum permissible value for α is 1 and 0.72 when $U = 2$ and 3, respectively. Although α-fairness JT-NOMA scheme can enhance user fairness dramatically when $U = 2$, its fairness performance degrades significantly when $U > 2$. This solicits for an alternative JT-NOMA scheme to enhance user fairness when serving more UEs.

III. Product-Rate-Based JT-NOMA

In order to enhance the user fairness when serving more UEs, a new objection function is designed here for the throughput maximization problem. In previous formulation, the sum rate $R_{\text{sum}} = \sum_{u \in \mathcal{U}} R_u$ was adopted as the object function. In virtue of the relationship that the arithmetic mean is greater than or equal to the geometric mean with the equality holding if and only if (iff) all terms involved are equal, it is straightforward that $R_{\text{sum}} / U \ge (R_{\text{product}})^{1/U}$ where the equality holds good iff all UEs have the same data rate, where $R_{\text{product}} = \prod_{u \in \mathcal{U}} R_u$ is referred to as the product rate for the NOMA system. Given a fixed R_{sum}, the maximum R_{product} occurs iff all individual rates R_u's are equal. This implies that all individual rates approach each other when the product rate R_{product} is maximized even though R_{sum} is not fixed. Therefore, the product rate R_{product} is adopted as the new objection function to formulate the maximization problem for the PR-based JT-NOMA scheme with an attempt to improving user fairness for CoMP networks serving more UEs. The total throughput maximization problem for PR-based JT-NOMA is thus formulated as in (4).

$$\begin{aligned} &\text{maximize} \quad R_{\text{product}} \\ &\text{Subject to} \quad \sum_{u=1}^{U} a_u = \frac{1}{B} \\ &\qquad\qquad\quad a_1 \ge \cdots \ge a_U \ge 0. \end{aligned} \tag{4}$$

IV. Peformance Results

In this section, Monte Carlo simulation is conducted on MATLAB to evaluate the performance characteristics of various JT-NOMA schemes. In the simulation, we consider the downlink CoMP system in which there are three single-antenna BSs and U single-antenna UEs. All UEs are randomly distributed within a circle of radius 0.25km at the origin $(0,0)$. The coordinates of BSs are respectively (1, 0), $(0.5, \sqrt{3}/2)$, and $(-0.5, -\sqrt{3}/2)$ in the km scale. All cells have the radius of 1km. The channel is modeled as $h_{b,u} = g_{b,u} d_{b,u}^{-v/2}$ where $g_{b,u}$'s are independent and identically distributed circularly symmetric complex Gaussian random variables with zero mean and unit variance, representing Rayleigh fades, $d_{b,u}$ is the distance from BS b to UE u, and the path loss exponent v is set to be 3. All channels are simulated 10 thousand times to provide accurate results. The performance results are characterized with respect to the signal-to-noise ratio (SNR) measure P/σ^2.

In the simulation, simple sub-optimal solutions are found for all throughput maximization problems. Specifically, all power allocation coefficients a_u's which satisfy their own constraints are randomly generated N times, and the system sum rate (or the product rate) is computed for each time. Among N trials, the largest sum rate (or product rate) as well as the corresponding UE rates are recorded. N is set to be 5000 in the simulation.

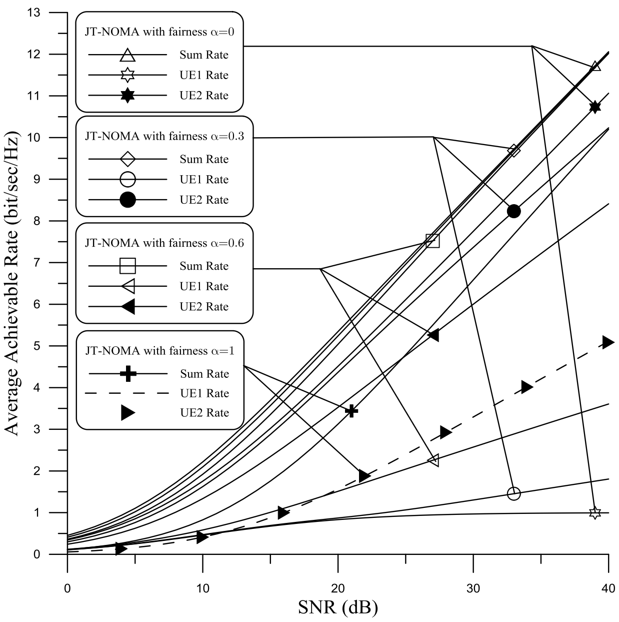

Fig. 2. Average achievable data rate characteristics provided by SR-based JT-NOMA with various α values when $U = 2$.

Fig. 2 shows the sum rate and individual UE rates of sum-rate-based (SR-based) JT-NOMA with various fairness factors when $U = 2$. As observed, the proposed α-fairness JT-NOMA scheme can still provide achievable sum rate performance comparable to conventional JT-NOMA (with $\alpha=0$) while yielding better user fairness when α approaches to 1. The α-fairness JT-NOMA scheme is shown to provide flexible user fairness by adjusting the factor α. Notably, the user fairness becomes better by increasing α and the ideal fairness can be achieved by setting α=1.

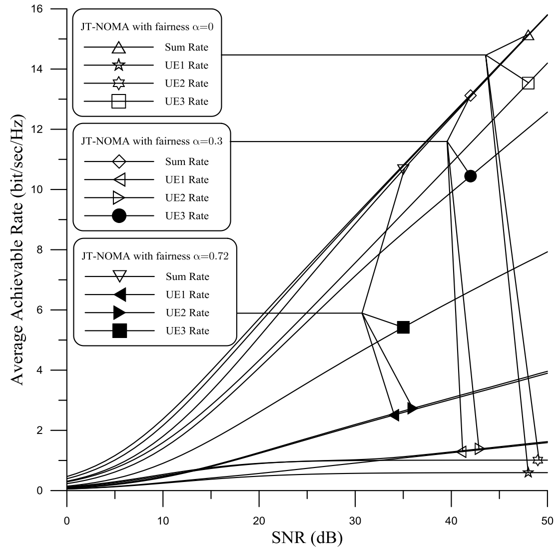

Fig. 3. Average achievable data rate characteristics provided by SR-based JT-NOMA with various α values when $U = 3$.

Fig. 3 also shows the average sum rate and individual UE rates of SR-based JT-NOMA with various fairness factors when $U = 3$. It can be observed that the α-fairness JT-NOMA can still provide achievable sum rate performance comparable to conventional JT-NOMA, while yielding better user fairness when α is set large. Unfortunately, the solution of the maximization problem in (3) does not exist when α is set larger than 0.72 for the considered SNR region. This limits the use of α-fairness JT-NOMA to downlink CoMP networks serving more NOMA UEs with sufficient fairness.

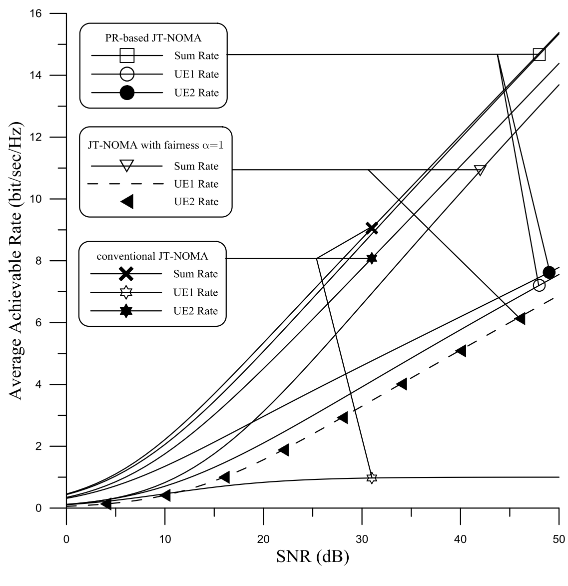

Fig. 4. Average achievable data rate characteristics provided by conventional JT-NOMA, SR-based JT-NOMA with α=1, and PR-based JT-NOMA when $U = 2$.

Fig. 4 shows the average sum rate and individual user data rates of conventional JT-NOMA, SR-based JT-NOMA with ideal fairness α=1, and PR-based JT-NOMA when $U = 2$. As shown, the SR-based JT-NOMA with ideal fairness α=1 and the PR-based JT-NOMA outperforms the conventional JT-NOMA remarkably in user fairness while providing comparable achievable sum rate performance. Moreover, the PR-based JT-NOMA can provide comparable user fairness to the SR-based JT-NOMA with ideal fairness when $U = 2$.

Fig. 5 shows the average sum rate and individual user data rates of the SR-based JT-NOMA with fairness α=0.72 and the PR-based JT-NOMA when $U = 3$. It is shown that the PR-based JT-NOMA outperforms the SR-based JT-NOMA with fairness α=0.72 both in achievable sum rate and in user fairness. Apparently, an increase in the number of UEs affects the user fairness performance significantly in the α-fairness JT-NOMA scheme but not remarkably in the PR-based JT-NOMA.

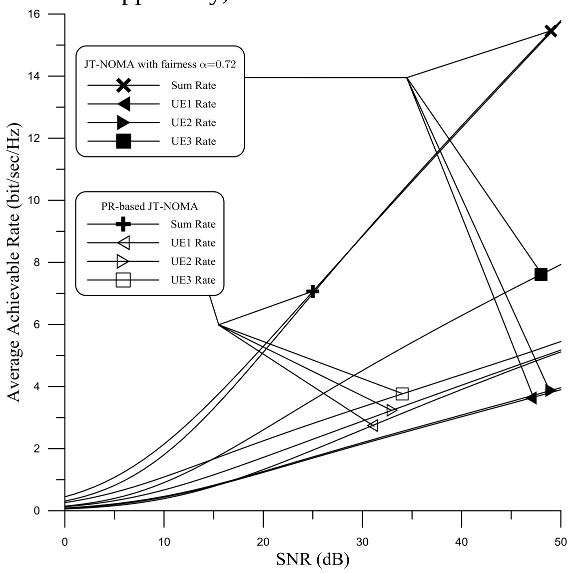

Fig. 5. Average achievable data rate characteristics provided by SR-based JT-NOMA with various α=0.72 and PR-based JT-NOMA when $U = 3$.

V. Conclusions

In this paper, α-fairness JT-NOMA scheme and product-rate-based JT-NOMA scheme are proposed to enhance the user fairness in downlink CoMP networks. Simulation results show that both schemes can provide comparable achievable sum rate performance to conventional JT-NOMA while yielding better user fairness. The α-fairness JT-NOMA scheme can provide flexible user fairness by adjusting the factor α. Particularly, PR-based JT-NOMA outperforms α-fairness JT-NOMA in achievable sum rate and user fairness when there are more than two UEs in the downlink CoMP system.

Acknowledgment

This work was supported by the Ministry of Science and Technology of Taiwan, under Grant MOST 106-2221-E-002-026-MY3.

References

[1] V. Jungnickel, K. Manolakis, W. Zirwas, B. Panzner, V. Braun, M. Lossow, M. Sternad, R. Apelfrojd, and T. Svensson, "The role of small cells, coordinated multipoint, and massive MIMO in 5G," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 44-51, May 2014.

[2] Z. Ding, Z. Yang, P. Fan, and H. V. Poor, "On the performance of non-orthogonal multiple access in 5G systems with randomly deployed users," *IEEE Signal Processing Letters*, vol. 21, no. 12, pp. 1501-1505, Dec. 2014.

[3] Y. Saito, Y. Kishiyama, A. Benjebbour, T. Nakamura, A. Li, and K. Higuchi, "Non-orthogonal multiple access (NOMA) for cellular future radio Aaccess," in *Proc. 77th Vehicular Technology Conference (VTC Spring)*, Jun. 2013, pp. 1-5.

[4] S. Timotheou and I. Krikidis, "Fairness for non-orthogonal multiple access in 5G systems," *IEEE Signal Processing Letters*, vol. 22, no. 10, pp. 1647-1651, Oct. 2015.

[5] J. Choi, "Power allocation for max-sum rate and max-min rate proportional fairness in NOMA," *IEEE Communications Letters*, vol. 21, no. 12, pp. 1501-1505, Dec. 2014.

[6] Z. Q. Al-Abbasi and D. K. C. So, "Power allocation for sum rate maximization in non-orthogonal multiple access system," in *Proc. 26th Annu. International Symposium on Personal Indoor and Mobile Radio Communications*, Hong Kong, 2015, pp. 1649-1653.

[7] J. Choi, "Non-orthogonal multiple access in downlink coordinated two-point systems," *IEEE Communications Letters*, vol. 18, no. 2, pp. 313-316, Feb. 2014.

[8] Y. Tian, A. R. Nix, and M. Beach, "On the performance of opportunistic NOMA in downlink CoMP networks," *IEEE Communications Letters*, vol. 20, no. 5, pp. 998-1001, May 2016.

[9] Z. Yang, W. Xu, C. Pan, and M. Chen, "On the optimality of power allocation for NOMA downlinks with individual QoS constraints," *IEEE Communications Letters*, vol. 21, no. 7, pp. 1649-1652, Jul. 2017.

Chia-An Ku was born in Taipei in 1993. He received the B.S. degree in electrical engineering from the National Chung Hsing University in Taiwan in 2016. He is currently studying for the M.S. degree in the Graduate Institute of Communication Engineering at the National Taiwan University.

Char-Dir Chung received the Ph.D. degree in electrical engineering from the University of Southern California, Los Angeles, in 1989. From 1989 to 1992, Dr. Chung was with the LinCom Corporation, Los Angeles. He joined the faculty of the National Central University (NCU) in Taiwan during 1992-2005. At NCU, he founded the Advanced Communication Laboratory in 1998, the Graduate Institute of Communication Engineering in 2000 and the Communication Engineering Department in 2003, and was the founding heads of these organizations. He has been on the faculty of the National Taiwan University since 2005, where he was endowed with the SiS Technology Chair in 2009 and Distinguished Professor since 2011. His current research interest is in digital modulation theory with particular emphasis in wireless communications. Dr. Chung is a Fellow of the IEEE.