Per User Based Interference Alignment for Uplink CoMP with Perfect CSI under Different Channel Models

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Abstract —Per-user based SLNR-SINR interference alignment (IA) algorithm for uplink CoMP is evaluated under different channel models. Rayleigh, Rician, and Nakagami fading channel is used in transmission with the Additive White Gaussian Noise (AWGN) channel set as reference. Performance evaluation is based on its achievable sum rate and convergence rate by varying the channel, the number of serving cells, and UE's transmit and receive antenna combination. Assuming perfect CSI, the result shows that the maximum achievable sum rate is when the communication occurs in the AWGN channel. There are 3 bps/Hz difference between communication over Rayleigh and Nakagami channel, and 1.5 bps/Hz difference between Rician and Nakagami channel. Among the three fading channels, a smaller number of transmitting and receiving antenna in UE resulted in a higher sum rate with 58.97 bps/Hz for IA in the Nakagami channel with {3, 2, 4, 4, 2} configuration. In the low SNR region, the lowest sum rate for this configuration achieves 15.87 bps/Hz for IA in the Rayleigh channel.

Index Terms—Interference alignment, uplink CoMP, sum rate, convergence

I. Introduction

The increasing number of mobile users pushes telecommunication providers to provide sufficient capacity to serve all its customers by implementing new technologies, establishing new base stations, increasing bandwidth, etc. Current technology deployed is the 4th Generation of wireless communication, LTE/A, which is designed to provide high transmission rates and low latency along with secure communication features [1]. Although LTE-A was developed to achieve higher network capacity than previous technology, users in cell boundaries susceptible to interference, not only due to their further distance from eNB serving the cell but also affected by Inter-Cell interference (ICI) and Co-Channel Interference (CCI) from users in the same cell and neighbors' [2].

Coordinated Multi-Point (CoMP) transmission and reception [3] has been proposed to improve system performance for cell-edge users that suffer from inter-cell interference. CoMP was first proposed by the Third Generation Partnership Project (3GPP) for LTE-A [4] to meet the requirement of system performance such as spectral efficiency and cell-edge user's throughput by giving resolution for supporting cell-edge completion while keeping the coordination complexity at a minimum level [2]. In CoMP operation, multiple points, in the forms of cells/base stations/mobile stations, coordinate with each other such that signals transmission among them spared from serious interference [5].

CoMP in downlink is divided into three main techniques, coordinated scheduling and coordinated beamforming (CS/CB), joint transmission (JT), and transmission point selection (TPS), while for uplink consists of two techniques, Coordinated Scheduling (CS) and Joint Reception and Processing (JR). CoMP-JR is proven to accommodate cell edge users in overlapping areas by increasing their spectral efficiency gain [6] (see Fig. 1 and Fig. 2).

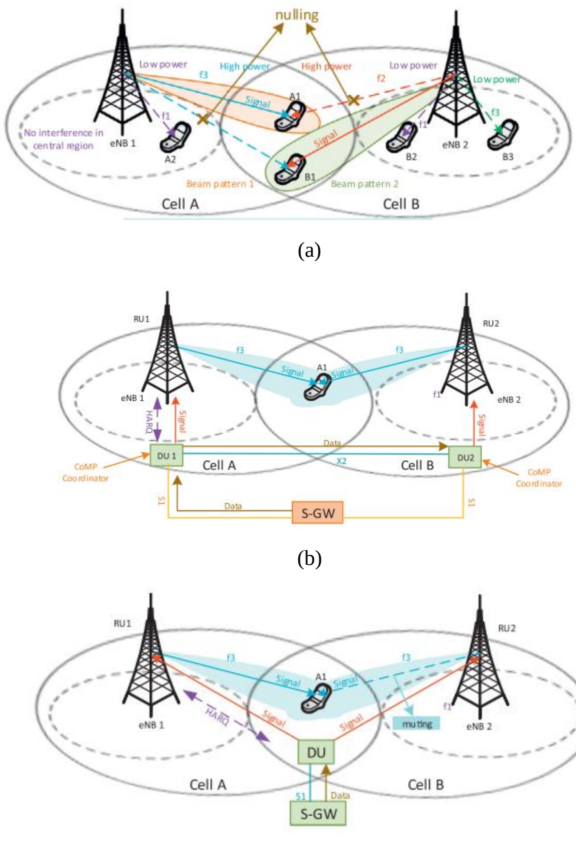

Fig. 1. CoMP downlink scenario (a) CS/CB (b) JT (c) TPS [2]

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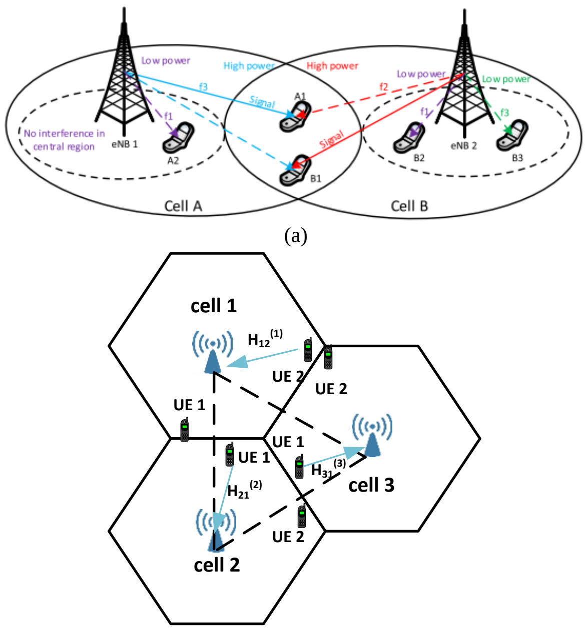


(a)

(b)

Fig. 2. CoMP uplink scenario (a) CS [2] (b) JR [7]

Interference alignment (IA), a method first proposed in [8], is a transmission strategy for the interference channel that results in sum capacities that scale linearly. It aligns signals over one of the three-dimension; time, space, or frequency such that multiplexing gain is reduced. Precoders-decoders combination is constructed such that the interference will align in one direction and resulting in in the existence of interference-free subspaces for information containing signals [9]. Due to the nature of CoMP, IA is needed to remove the interferences for cell-edge users. Many works evaluate IA performance. The earliest precoder and decoder design for IA is proposed in [10], [11]. Recent advantages are shown in [12]. The authors propose a method to predict channel state information (CSI) rather than gathering CSI through feedback. On the other hand, [13] implements a precoding-decoding algorithm to align the interference coming from the same source. However, those design is implemented for MIMO Interference channel, where inter-cell interference is ignored.

In CoMP, IA performance shows a significant result in combating interference. In the downlink side, IA methods of [14] used Signal to Leakage and Noise Ratio (SLNR) based precoding to achieve a lower bit error rate (BER) compared to block diagonalization and linear precoders. In [15], the authors studied the asynchronous distributed iterative method based on multipliers' alternation distribution method to update the MMSE precoder's weight.

On the other hand, [6] presents a comparative study of several non-IA uplink CoMP methods. At the same time, [16] proposed a lower complexity IA method that could achieve the same performance as an exhaustive method for uplink CoMP. However, using combined criteria of SLNR and Signal to Interference and Noise Ratio (SINR) for each user, authors in [7] achieved higher sum rate for uplink CoMP in Additive White Gaussian Noise (AWGN) channel.

Although AWGN channel is mainly used as a communication channel over simulation, in reality, flat and multipath fading often occurs in radio communications [17]. Multipath fading happened due to the constructive and destructive combination of randomly delayed, reflected, scattered, and diffracted signal components [18]. There are several statistical models of multipath fading, includes Rayleigh, Rician, and Nakagami Model.

This study evaluates the performance of methods used in [7] under different channel models. Using AWGN as a reference, we evaluate the performance of the proposed methods in Rayleigh, Rician, and Nakagami channel models with different cell sizes and antenna combination.

The rest of this paper is organized as follows. System model is described in Chapter II. Chapter III evaluates the simulation results, and the conclusion is given in Chapter IV.

II. System Models

Using the same simulation environment and scenario as [7], we evaluate the proposed method's performance under different channel models. Refer to Fig. 3, supposed C is the number of cell-sites that cooperatively serve K cell edge users per cell. $\mathbf{x}_k^{(c)} \in \mathbb{C}^{d\times 1}$ notes data streams d that sent from each user k in cell index c. Transmit power of each user is calculated as $E\left\{\mathbf{x}_k^{(c)H}\mathbf{x}_k^{(c)}\right\} = p_k^{(c)}$.

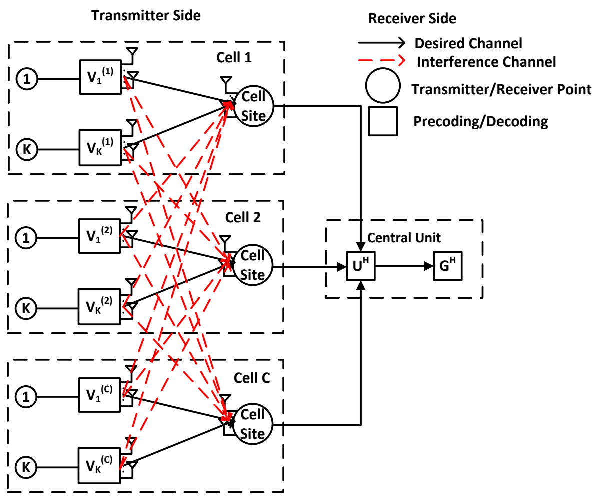


Fig. 3. Block diagram of interference alignment in uplink CoMP with C cells, each having K users [7].

The received signal $\mathbf{y}_c \in \mathbb{C}^{N\times 1}$ in cell site c can be expressed as

$$\mathbf{y}_c = \sum_{k=1}^{K}\mathbf{H}_{c,k}^{(c)}\mathbf{V}_k^{(c)}\mathbf{x}_k^{(c)} + \sum_{m=1,m\neq c}^{C}\sum_{k=1}^{K}\mathbf{H}_{c,k}^{(m)}\mathbf{V}_k^{(m)}\mathbf{x}_k^{(m)} + \mathbf{n}_c, \quad (1)$$

where M and N is the number of transmit and receive antenna, respectively, $\mathbf{H}_{c,k}^{(m)}$ is the matrix channel from user k in cell m to cell c.

Channel matrix $\mathbf{H}$ is differentiated for each fading channel model. In Rayleigh channel, $\mathbf{H}$ is a random complex matrix following Gaussian distribution with no Line of Sight (LOS) component, while Rician fading is Rayleigh with LOS component. Gamma distribution is used for Nakagami fading channel, and AWGN is set as the reference with its linear distribution [18].

Pdf of Rayleigh, Rician, and Nakagami channel is shown in equation (2) [19], (3) [19], (4)[18] respectively.

$$f_X(x) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}} \quad (2)$$

$$f_X(x) = \frac{x}{\sigma^2} e^{-\frac{x^2+r_c^2}{2\sigma^2}} I_0\left(\frac{x r_c}{\sigma^2}\right) \quad (3)$$

$$f_{X(x)} = \frac{2m^m x^{2m-1}}{\sigma^{2m}\Gamma(m)} e^{-\frac{mx^2}{\sigma^2}} \quad (4)$$

where $2\sigma^2 = E\{X^2\}, X^2$ is a chi-square random variable and σ^2 is the variance of Gaussian random variables with zero mean. In Rician fading, r_c represents the LOS component, and $I_0\langle\cdot\rangle$ is the modified zeroth-order Bessel function of the first kind. On the other hand, Nakagami channel used gamma distribution based random variables with m is Nakagami fading parameter, ranging from $\frac{1}{2}$ to ∞. In this paper, the value of m is set to be random number between 1 and ∞.

$M \times d$ precoding matrix of this user is denoted as $\mathbf{V}_k^{(c)}$, and the noise vector observed during transmission to cell site c is denoted as $\mathbf{n}_c$. From [7], precoding matrix is designed as $\mathbf{V}_k^{(c)} = \widetilde{\mathbf{V}}_k^{(c)}/\|\widetilde{\mathbf{V}}_k^{(c)}\|$ with $\widetilde{\mathbf{V}}_k^{(c)}$is stated in (5).

$$\widetilde{\mathbf{V}}_k^{(c)} = \overline{eig}_d\left(\left(\mathbf{Q}_k^{(c)}\right)^{-1}\left(\mathbf{H}_k^{(c)H}\mathbf{U}_k^{(c)}\mathbf{U}_k^{(c)H}\mathbf{H}_k^{(c)}\right)\right) \quad (5)$$

$\mathbf{Q}_\text{k}^{(c)}$ is a matrix derived from the SLNR equation, which is the criterion used to align the interferences.

With CoMP model, all signals will be grouped and processed as

$$\mathbf{y} = \mathbf{HVx} + \mathbf{n} \quad (6)$$

where $\mathbf{y}$ is the row vector consists of all received signals in the propagation, $\mathbf{H}$ is the $CN \times CKM$ concatenated channel matrix, $\mathbf{V}$ is block diagonal matrix, which its diagonal value is the groups of precoding matrix used in the system. The noise vector is merged as $\mathbf{n}$ matrix with σ^2 as the variance.

In the receiver, $CN \times d$ decoding matrix $\mathbf{U}_k^{(c)} = \widetilde{\mathbf{U}}_k^{(c)}/\|\widetilde{\mathbf{U}}_k^{(c)}\|$ is used to align the interferences in user k from cell c, where $\widetilde{\mathbf{U}}_k^{(c)}$ is stated in (7). Max SINR is the decoder criterion, and thus matrix $\mathbf{B}_k^{(c)}$ is the derivation from the SINR equation. Decoder matrices from all users in all cells are grouped as $CN \times CKd$ matrix $\mathbf{U}$.

$$\widetilde{\mathbf{U}}_k^{(c)} = \overline{eig}_d\left(\left(\mathbf{B}_k^{(c)}\right)^{-1}\left(\mathbf{H}_k^{(c)}\mathbf{V}_k^{(c)}\mathbf{V}_k^{(c)H}\mathbf{H}_k^{(c)H}\right)\right) \quad (7)$$

Utilizing the MMSE MIMO detection method, the detected symbol is described by

$$\hat{\mathbf{x}} = \mathbf{G}^\text{H}\mathbf{z} = \mathbf{G}^\text{H}\mathbf{H}_\text{eq}\mathbf{x} + \mathbf{G}^\text{H}\tilde{\mathbf{n}}, \quad (8)$$

where $\mathbf{H}_\text{eq} = \mathbf{U}^\text{H}\mathbf{HV}$ and $\mathbf{G}^\text{H}$ is the MMSE matrix used to detect received symbol.

Following [9], the total achievable sum rate is defined as

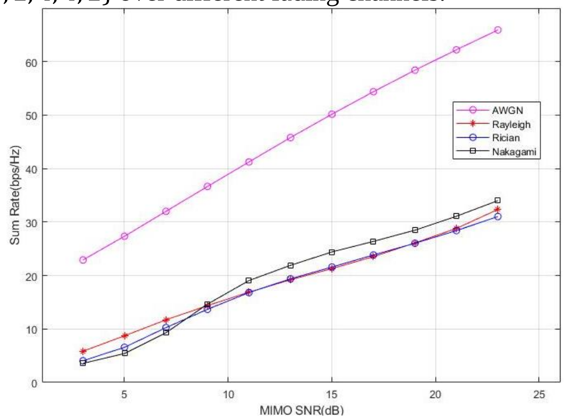
$$R_{sum} = \sum_{i=1}^{CKd} \log_2(1 + SINR_i), \quad (9)$$

and $SINR_i$ of the stream i is given by,

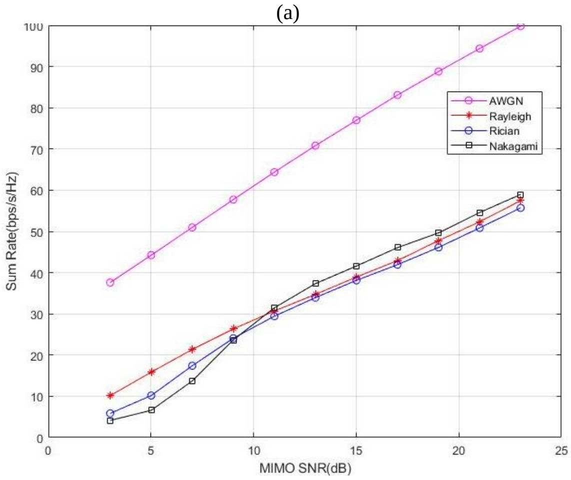
$$SINR_i = \frac{\mathbf{G}_i^\text{H}\mathbf{H}_{\text{eq},i}\mathbf{H}_{\text{eq},i}^\text{H}\mathbf{G}_i}{\sum_{l\neq i}\mathbf{G}_i^\text{H}\mathbf{H}_{\text{eq},l}\mathbf{H}_{\text{eq},l}^\text{H}\mathbf{G}_i + \sigma^2\mathbf{G}_i^H\mathbf{G}_i} \quad (10)$$

III. Results and Discussion

Perfect channel state information (CSI) availability means that the receiver is aware of fading's realization. The assumption of CSI is used in order to simplify the simulation and obtain first insight into this problem. [20] stated that perfect CSI facilitates the channel capacity significantly using multiple transmitter and receiver antennas. Implementing this assumption, we simulate per user based combined SLNR SINR IA method in Rayleigh, Rician, and Nakagami fading channel. Supposed we have $\{C, K, M, N, d\}$ denote the CoMP configuration. Fig. 4. shows the achievable sum rate of (a) $\{2, 2, 4, 4, 2\}$, and (b) $\{3, 2, 4, 4, 2\}$ over different fading channels.



(a)

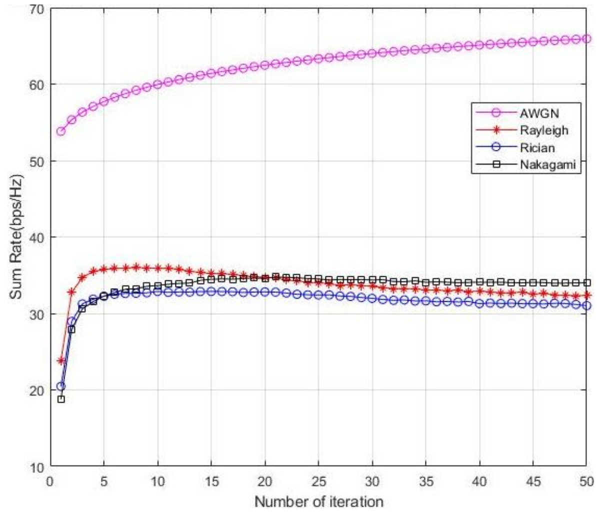


(b)

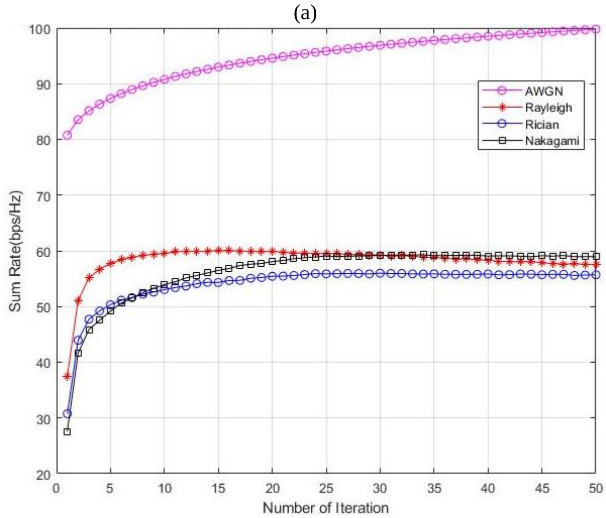
Fig. 4. Achievable sum rate of IA in uplink CoMP with (a) $\{2, 2, 4, 4, 2\}$ (b) $\{3, 2, 4, 4, 2\}$ configuration

Methods in the AWGN channel achieves a higher sum rate than others since channel distribution is simply linear. Comparing Rayleigh and Rician, transmission over Rayleigh channel has better performance than Rician, since there is no LOS component in Rayleigh channel. On the other hand, transmission through Nakagami provides a higher sum rate in higher SNR than Rayleigh and Rician with the average difference reaches 3 bps/s/Hz. In the low SNR region, there is 3 bps/Hz difference between the implementation of the IA method in Nakagami and Rayleigh channel, while 1.5 bps/Hz with a Rician channel. In SNR = 9 dB, transmission in the Nakagami channel starts to precede Rayleigh and Rician.

A higher sum rate is achieved when the system has higher serving cells. In a scenario with two serving cells, the highest achievable sum rate is 65.93 bps/Hz, which is happened in transmission via the AWGN channel. However, with 3 serving cells, the highest achievable sum rate increasing 50% to 99.79 bps/Hz. In cell edge users case, when there are more serving cells available, their throughput tends to be higher, since the available communication channel that connects them to other users is larger.



(a)



(b)

Fig. 5. The convergence of IA method in uplink CoMP with (a) $\{2, 2, 4, 4, 2\}$ (b) $\{3, 2, 4, 4, 2\}$ configuration

Since it is an iterative method, convergence is analyzed. Fig. 5 shows the convergence of (a) $\{2, 2, 4, 4, 2\}$ (b) $\{3, 2, 4, 4, 2\}$ configuration. At least 25 iterations are needed for transmission in Nakagami while Rayleigh and Rician only require less than 15 iterations from both configurations. The complexity is the reason for this phenomenon. PDF formula of Nakagami and its gamma distribution requires more iterations to reach a stable value. On the other hand, Rayleigh and Rician use less simple distribution, which is Gaussian.

In light of the number of transmitting and receiving antenna in mobile users, the sum rate of scenario with fewer UE's antenna is higher, as shown in Fig. 6.

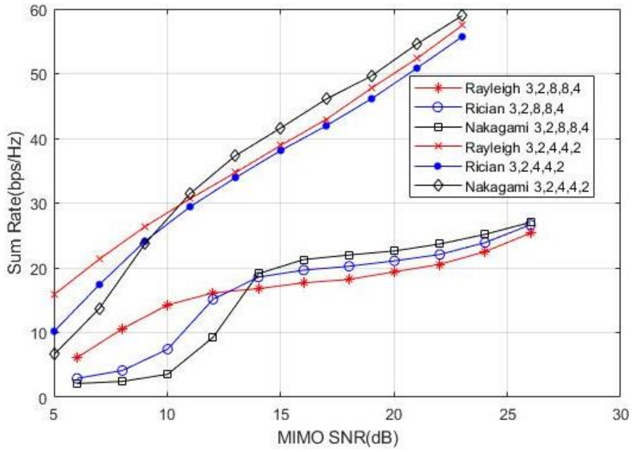


Fig. 6. Achievable sum rate of IA in uplink CoMP with a different number of UE's antenna.

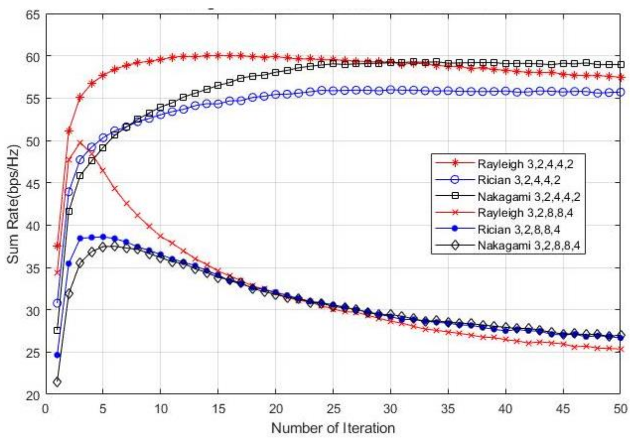


Fig. 7. The convergence of 3 Cells 2 users IA in CoMP with different number of UE's antenna

When the number of UE's antenna is high, the number of generated channels is also high; thus, the probability of interference could happen is high. In 4×4 UE's antenna configuration, the generated channels are $4 \times 4 = 16$ channels, while in 8×8 are 64 channels. A large number of channels could increase the possibilities of interference. However, if the number of eNB's antenna is high, the sum rate will most likely be higher because the serving channel is also larger.

Fig. 7 depicts the IA method's convergence with the different numbers of UE's antenna under different channel models. The smaller number of UE's antenna, the faster it achieves convergence. Since larger interference channels need to be aligned, the IA method needs more iteration to achieve convergence in a higher number of UE's antenna.

Regardless of the number of cells, the number of UE's antenna, and fading channel scenario, the IA method in uplink CoMP achieves a higher sum rate, especially for cell-edge users compared to LTE-A standard in [21]. It means that the implementation of IA could improve the performance of CoMP.

IV. Conclusion

In this study, we evaluated per user based IA method in uplink CoMP under different channel models. The best scenario to achieve the highest sum rate uses {3,2,4,4,2} configuration under the AWGN channel. IA methods transmitted in Rayleigh channel excels in the lower SNR region than Rician and Nakagami. On the other hand, in the higher SNR region, the IA method transmitted in the Nakagami channel is proven to have a better sum rate. A lower number of UE's antenna achieves a higher sum rate, but the effect of eNB's antenna combination needs to be investigated further.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Amalia Eka Rakhmania is the leading researcher and corresponding author for this project, responsible for simulating and analyzing the result. Mochammad Taufik and Hudiono Hudiono contributed to the antenna simulation and analysis, Ridho Hendra Yoga Perdana formulating the simulation environment and system evaluation. All authors had approved the final version.

References

[1] D. Rupprecht, K. Kohls, T. Holz, and C. Popper, "Breaking LTE on Layer Two," *Proc. - IEEE Symp. Secur. Priv.*, vol. 2019-May, pp. 1121–1136, 2019.

[2] F. Qamar, K. B. Dimyati, M. N. Hindia, K. A. Bin Noordin, and A. M. Al-Samman, "A comprehensive review on coordinated multi-point operation for LTE-A," *Comput. Networks*, vol. 123, no. March 2018, pp. 19–37, 2017.

[3] M. Sawahashi, Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, "Coordinated multipoint transmission/reception techniques for LTE-advanced," *IEEE Wirel. Commun.*, vol. 17, no. 3, pp. 26–34, 2010.

[4] 3GPP Organizational Partners, "3GPP TR 36.819 V11.2.0," 2013.

[5] J. Lee, *et al.*, "Coordinated multipoint transmission and reception in LTE-advanced systems," *IEEE Commun. Mag.*, vol. 50, no. 11, pp. 44–50, 2012.

[6] R. Annavajjala, "Low-complexity distributed algorithms for uplink CoMP in heterogeneous LTE networks," *J. Commun. Networks*, vol. 18, no. 2, pp. 150–161, 2016.

[7] A. E. Rakhmania, P. Y. Tsai, and O. Setyawati, "Combined per-user SLNR and SINR criterions for interference alignment in uplink coordinated multi-point joint reception," in *Proc. Asia-Pacific Signal Inf. Process. Assoc. Annu. Summit Conf. APSIPA 2014*, 2014.

[8] V. R. Cadambe and S. A. Jafar, "Interference alignment and spatial degrees of freedom for the K user interference channel," in *Proc. IEEE Int. Conf. Commun.*, vol. 54, no. 8, 2008, pp. 971–975.

[9] O. El Ayach, S. W. Peters, and R. W. Heath, "The feasibility of interference alignment over measured MIMO-OFDM channels," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4309–4321, 2010.

[10] K. Gomadam, V. R. Cadambe, and S. A. Jafar, "A distributed numerical approach to interference alignment and applications to wireless interference networks," *IEEE Trans. Inf. Theory*, vol. 57, no. 6, pp. 3309–3322, 2011.

[11] C. Wilson and V. Veeravalli, "A Convergent version of the max SINR algorithm for the MIMO interference channel," *IEEE Trans. Wirel. Commun.*, vol. 12, no. 6, pp. 2952–2961, 2013.

[12] S. Pramono, E. Triyono, and B. B. Subagio, "Performance of leakage based precoding scheme for minimizing interference," *J. Commun.*, vol. 15, no. 2, pp. 214–220, 2020.

[13] Z. Li, Y. Bai, K. G. Shin, Z. Yan, and H. Li, "Inside-Out precoding to manage multiple interferences from the same source," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 1–1, 2020.

[14] Z. Li, Y. Liu, Y. Zhang, P. Wang, C. Tian, and X. Sha, "Hybrid coordinated strategy of downlink coordinated multi-point transmission," *J. Syst. Eng. Electron.*, vol. 26, no. 5, pp. 916–923, 2015.

[15] Z. Wu and Z. Fei, "Precoder design in downlink CoMP-JT MIMO network via WMMSE and asynchronous ADMM," *Sci. China Inf. Sci.*, vol. 61, no. 8, pp. 1–13, 2018.

[16] M. C. Lee, C. J. Huang, W. H. Chung, and T. S. Lee, "A low complexity configuration selection algorithm in IA-aided uplink coordinated multipoint systems," *IEEE Veh. Technol. Conf.*, vol. 2015-January, no. January, 2014.

[17] G. Sadeque, S. C. Mohonta, and F. Ali, "Multipath rayleigh and rician fading channel simulation using MATLAB," *Am. J. Eng. Res. (AJER)*, vol. 4, no. 6, pp. 36–42, 2015.

[18] M. K. Simon and M. S. Alouini, *Digital Communication over Fading Channels: Second Edition*, 2005.

[19] Y. S. Choo, J. Kim, W. Y. Yang, and C. G. Kang, *MIMO-OFDM Wireless Communications with MATLAB*, SIngapore: John Wiley & Sons (Asia) Pte Ltd, 2010.

[20] T. Koch, "Is the assumption of perfect channel-state information in fading channels a good assumption?" in *Proc. 2nd Int. Symp. Appl. Sci. Biomed. Commun. Technol. ISABEL 2009*, 2009.

[21] I. F. Akyildiz, D. M. Gutierrez-Estevez, and E. C. Reyes, "The evolution to 4G cellular systems: LTE-Advanced," *Phys. Commun.*, vol. 3, no. 4, pp. 217–244, 2010.

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