Mobility-aware null-space expansion for multiuser massive MIMO

Nobutaka Funaki$^1$.a), Kazuki Maruta$^2$.b), and Chang-Jun Ahn$^1$

$^1$Graduate School of Science and Engineering, Chiba University
1–33 Yayoi-cho, Inage-ku, Chiba 263-8522, Japan

$^2$Academy for Super Smart Society, Tokyo Institute of Technology
Tokyo 152–8552, Japan

a) nobutaka.funaki@chiba-u.jp
b) kazuki.maruta@m.ieice.org

Abstract: This letter proposes adaptive null-space expansion (NSE) for multiuser massive MIMO according to users’ mobility. NSE can improve the robustness of multi-user spatial multiplexing in a time-varying channel by expanding null-steering to multiple past channels. Its superiority was verified under the unified moving speed among users. In a realistic environment, users with different speeds coexist. Null-space dimension, which is the number of nullified channels per user terminal, should be optimized in accordance with users’ mobility so as to maximize the beamforming gain and nullification capability. In our proposal, we first show that user mobility can be classified by observing the singular value of time-varying channels. Computer simulation then clarifies that output SINR can be improved by assigning null space dimensions respective to user moving speeds.

Keywords: multiuser MIMO, inter-user interference, time-varying channel, massive MIMO

Classification: Wireless Communication Technologies

References

[1] Y. Takatori and K. Nishimori, “Application of downlink multiuser MIMO transmission technology to next generation very high throughput wireless access systems,” IEICE Trans. Commun., vol. J93-B, no. 9, pp. 1127–1139, Sept. 2010.

[2] E.G. Larsson, O. Edfors, F. Tufvesson, and T.L. Marzetta, “Massive MIMO for next generation wireless systems,” IEEE Commun. Mag., vol. 52, no. 2, pp. 186–195, Feb. 2014. DOI: 10.1109/MCOM.2014.6736761

[3] K. Yamaguchi, H.P. Bui, Y. Ogawa, T. Nishimura, and T. Ohgane, “Channel prediction techniques for a multi-user MIMO system in time-varying environments,” IEICE Trans. Commun., vol. E97-B, no. 12, pp. 2747–2755, Dec. 2014. DOI: 10.1587/transcom.E97.B.2747

[4] T. Iwakuni, K. Maruta, A. Ohta, Y. Shirato, T. Arai, and M. Iizuka, “Null-space expansion for multiuser massive MIMO inter-user interference suppression in time varying channels,” IEICE Trans. Commun., vol. E100-B, no. 5, pp. 865–873, May 2017. DOI: 10.1587/transcom.2016EBP3136

[5] K. Arai, K. Maruta, and C.-J. Ahn, “Uplink null-space expansion for multiuser massive MIMO in time-varying channels under unknown interference,”
1 Introduction

Due to the rapid proliferation of wireless communication devices, the volume of mobile traffic is growing rapidly. There is a need for wireless communication technology to accommodate this explosion. In LTE Advanced, multiuser MIMO technology has been introduced, which performs spatial multiplexing to communicate with multiple users on the same frequency resource simultaneously [1]. Further, the technical concept on 5G and beyond extends it towards the massive MIMO, in which the number of antenna elements at the base station (BS) is excessively larger than the total that at the user terminals (UTs) side [2]. Massive MIMO has high beamforming and interference suppression (null-steering) capabilities thanks to plentiful spatial degrees of freedom (DoF). Its spatial multiplexing performance, i.e., beamforming and nullification balancing, can be controlled by the array weight design. To calculate pre/post-coding weights requires channel state information (CSI) between BS and UTs. Especially in downlink transmission, there is a problem that UTs mobility after CSI acquisition on the BS side causes the channel aging failing null-steering. This impact limits the output signal-to-interference-plus-noise power ratio (SINR) at the UT side. For this reason, in order to overcome the adverse effects of UT movement, channel prediction methods have been investigated [3]. Furthermore, by fully exploiting DoF of massive MIMO, the null-space expansion (NSE) was developed that outperforms channel prediction approaches [4, 5]. Expanding null-steering to multiple past channels can improve the robustness of multi-user spatial multiplexing against the UT movement. The number of nullified channels per UT is called the null-space dimension. The previous study suggested that the appropriate number of null-space dimensions for each UT speed exist since the time variation of the channel depends on UT’s speed [4]. Evaluations on NSE so far have been under unified UT speed, however, they vary in a realistic environment.

Thus, in this letter, we propose an extension of the null-space expansion method for environments where UTs with different speeds coexist. The major contributions of this letter are as follows. 1) User mobility can be discriminated against by observing the singular value of time-varying channels. 2) Output SINR can be improved by assigning a null space dimension respective to user moving speeds.

2 System model

In this paper, we consider a downlink multiuser massive MIMO system in a time-varying channel environment as shown in Fig. 1. BS having $N_T$ antenna elements transmits signals simultaneously to the $N_U$ UTs with single antenna. The downlink
channel matrix between BS and UTs at any given time $n$ is expressed as
\[ H[n] = \begin{bmatrix} h_1[n], & \ldots, & h_i[n], & \ldots, & h_{N_U}[n] \end{bmatrix}^\top, \]
(1)
where $h_i[n] \in \mathbb{C}^{N_T \times 1}$ represents the channel vector between BS antennas and the $i$-th UT and varies with the time $n$.

Fig. 1. System model of multiuser massive MIMO.

3 Proposal: mobility-aware null-space expansion

In our proposed method, we first classify UTs by their moving speeds and then calculate precoding weights with different null-space dimensions for each group.

3.1 User terminal classification based on singular value analysis

For simplicity, we assume that there are two patterns of UTs’ speeds, and they are classified into two groups. Let $M$ denote the number of past observations, we construct the following time-series channel matrix $H_i[n] \in \mathbb{C}^{N_T \times M}$ for each $i \in \{1, \ldots, N_U\}$;
\[ H_i[n] = [h_1[n], \ldots, h_i[n-m], \ldots, h_i[n-M+1]]^\top. \]
(2)

Then, we can observe the principal subspace’s dimension of the time-varying channel by decomposing this time-series channel matrix into singular values.
\[ H_i[n] = U_i[n] \Sigma_i[n] V_i^H[n], \]
(3)
where,
\[ \Sigma_i[n] = \text{diag}(\sigma^{(i)}_1, \sigma^{(i)}_2, \ldots, \sigma^{(i)}_M). \]
(4)

Here, if $\sigma^{(i)}_1 \geq \sigma^{(i)}_2 \geq \cdots \geq \sigma^{(i)}_M$, UT classification is performed by comparing the magnitude of minimum singular value $\sigma^{(i)}_M$ among UTs. These are sorted in descending order;
\[ \sigma^{(s(1))}_M \geq \sigma^{(s(2))}_M \geq \cdots \geq \sigma^{(s(N_U))}_M, \]
(5)
where \( \{s(1), s(2), \ldots, s(N_U)\} = \{1, 2, \ldots, N_U\} \). The larger value of $\sigma^{(i)}_M$ represents higher mobility. If we set the number of UTs in the group $G_1$ to $L$, we classify them as \( \{s(1), s(2), \ldots, s(L)\} \in G_1 \) and \( \{s(L+1), s(2), \ldots, s(N_U)\} \in G_2 \). The number of UTs in each group can be flexible; thresholding is also capable as a condition for classification.
3.2 Precoding weight calculation by null-space expansion

Null-space dimension to be expanded can be determined for each mobility group. A general principle is to assign the lower null-space dimension to lower speed UTs involved in a slow channel variation and vice versa. According to the above grouping, high-speed UTs are included in $G_1$, and low-speed UTs are included in $G_2$, so the precoding weights are calculated as described below. The extended channel for designing precoding weight is configured for each UT.

$$\tilde{H}_i[n] = [h_i[n], \tilde{H}_1[n], \ldots, \tilde{H}_{i-1}[n], \tilde{H}_{i+1}[n], \ldots, \tilde{H}_{N_U}[n]]^\top,$$

where each $\tilde{H}_j[n]$ ($j \neq i$) are determined based on the aforementioned grouping:

$$\tilde{H}_j[n] = \begin{cases} [h_j[n], h_j[n-1], \ldots, h_j[n-N_1+1]]^\top & (j \in G_1) \\ [h_j[n], h_j[n-1], \ldots, h_j[n-N_2+1]]^\top & (j \in G_2). \end{cases}$$

It indicates that the $N_1$-dimensional null space is assigned to high-speed UTs and the $N_2$-dimension to low-speed UTs. Precoding weight for the $i$-th UT is calculated based on the extended channel. There are various methods for designing precoding weights; for example, minimum mean square error (MMSE) manner provides,

$$W_i[n] = \tilde{H}_i[n]^H (\tilde{H}_i[n]\tilde{H}_i[n]^H + \gamma I)^{-1},$$

where $\gamma$ denotes the reciprocal of the downlink signal-to-noise power ratio (SNR). Let $w_1^{(i)}[n] \in \mathbb{C}^{N_T \times 1}$ ($i = 1, \ldots, N_U$) be the vector in the first column of $W_i[n]$, precoding weight matrix is finally expressed as follows.

$$W[n] = [w_1^{(1)}[n], \ldots, w_1^{(i)}[n], \ldots, w_1^{(N_U)}[n]].$$

4 Simulation result

Representative parameters are listed in Table I and are basically compliant with [4]. The simulation assumes the same and invariant SNR for all UTs. Suppose the knowledge of the downlink SNR, we employ MMSE precoding. The number of past channel observations $M$ in Eq. (2) is set to 5. $N_U = 8$ UTs are classified into two groups, i.e. $L = 2$; 2 UTs in higher mobility and 6 in lower mobility. The comparison scheme is the conventional NSE, where the same null-space dimensions are expanded for all UTs. First, we confirm the feasibility of the proposed mobility classification. Figures 2(a)(b) show the cumulative distribution function (CDF) of normalized minimum singular values in Eq. (5) and autocorrelation coefficients with 1.8 msec interval for each UT. The latter is defined as follows.

$$r_i(\tau) = \frac{|h_i^H[n]h_i[m]|}{|h_i^H[n]| |h_i[m]|},$$

where $\tau = m - n$ corresponds to the interval. The objective of this observation is to evaluate the easiness or tendency of discriminating speed in each metric. The distribution of singular values is larger for high-speed UTs than that for low-speed ones because the substantial subspace dimension in which the channel varies is higher. Although difference can also be confirmed in distributions of autocorrelation coefficients with speeds, these are overlapped in most regions. This means that
Table I. Simulation parameters.

| Parameters                  | Values                                                                 |
|-----------------------------|------------------------------------------------------------------------|
| Frequency                   | 28 GHz                                                                 |
| Cell                        | Sector = 120°, Radius = 20 m                                          |
| BS antenna array            | 100 elements (10 × 10), Uniform planner array with half-wavelength spacing |
| BS antenna element          | Directional antenna, HPBW=65° (Vertical/Horizontal)                   |
| Number of UTs               | High-speed UT : 2, Low-speed UT : 6 (omnidirectional 1 element per UT) |
| UT speed                    | High-speed UT : 10 km/h, Low-speed UT : 4 km/h (f_D T_S = 2.3 ×10^{-3}, 9.3 ×10^{-4}) |
| Channel Model               | Rician fading, K = 10 dB                                              |
| Downlink SNR                | 20 dB                                                                  |
| Weight calculation interval | 200 symbols (1.8 msec)                                                |
| Symbol duration             | 8.93 μsec (Short GI, 7%)                                              |
| MIMO precoding weight       | MMSE                                                                  |

Fig. 2. Simulation results.

The singular value-based approach can provide superior discrimination accuracy. Furthermore, it can also be exploited to determine the optimal null-space dimensions based on the number of dominant singular values [6].

Figures 2(c)(d) present the signal-to-interference-plus-noise power ratio (SINR) characteristics of the fifth percentile and median values versus the null-space dimen-
sion for high-speed UTs $N_1$. Here, the null-space dimension assigned to low-speed UTs is fixed to $N_2 = 2$ (it is sufficient for their mobility) and that for high-speed UTs $N_1$ is variable. Figure 2(c) shows the SINR values of high-speed UTs. Maximal median SINR values for the proposal and the conventional NSE are 23.0 dB at $N_1 = 7$ and 21.8 dB at $N_1 = 4$, respectively. In this case, that of the fifth percentile are 10.3 dB and 7.8 dB. As can be seen, our proposed scheme can improve SINR performance for both high/low-speed UTs. Further, it is possible to keep a higher SINR than the conventional even though the null-space dimension is excessively expanded. Figures also plot SINR performances using autocorrelation coefficients for mobility discrimination. Here these accuracies are 97.7% for the proposed scheme while 73.1% for the autocorrelation based one. The accuracy means a percentage of correct selection of high-speed UTs among eight UTs. Suppose the number of high-speed UTs is known, the singular values or autocorrelation coefficients are sorted in descending order. The two largest are selected as high-speed UTs in the proposed scheme, and the two smallest are selected as high-speed UTs in the autocorrelation based one. The proposed scheme accurately classifies the user mobility and can perform adequate nullification resulting in better SINR performance.

Figure 2(d) shows the SINR values of low-speed UTs. Since low-dimensional nulls are sufficient to suppress interference for low-speed UTs, the SINR decreases as the null-space dimension expands. Nevertheless, the proposed scheme can alleviate such SINR depression compared to the conventional one.

From these results, it can be confirmed that the conventional scheme cannot assign appropriate null-space dimensions to each of the UT with different speeds. When trying to improve the SINR performance of high-speed UTs with the NSE approach, the SINR value of low-speed UTs is significantly degraded due to the consumption of DoF. On the other hand, our proposal can increase the null-space dimension only for high-speed UTs by discriminating UTs in terms of their mobility. Therefore, even if the null-space dimension is increased to improve the SINR performance of high-speed UTs, the degradation of SINR performance of low-speed UTs can be suppressed. It can well balance DoF consumption between beamforming and null-steering, resulting in overall SINR performance enhancement.

### 5 Conclusion

This letter proposed an extension of the null-space expansion scheme for multiuser spatial multiplexing under different moving speeds circumstances. Firstly, we classify UTs by discriminating their moving speed. It can be achieved by analyzing singular values of concatenated time-series channel vectors. Then, the null-space dimension is allocated appropriately to each mobility group. The simulation results verified its fundamental feasibility; the proposed scheme improves SINR performances in both high and low-speed UTs and effectively compensates for the SINR degradation in a higher null-space dimension regime. We can conclude that the proposed scheme provides stability of SINR against the expansion of the null-space dimension and ensures equality among UTs with different speeds.
Acknowledgments

This work was supported by the KDDI Foundation, the Mazda Foundation, and KAKENHI Grant-in-Aid for Scientific Research (B) (20H04178).