Initial Beam Selection Scheme Using Channel Correlation Matrix in mmWave Massive MIMO Systems

Jaemin Jung*, Heeyoung Kim*, Seongbae Han*, Youngrok Jang*, Seokki Kim†, Seungkwon Baek†, and Sooyong Choi*
*School of Electrical and Electronic Engineering, Yonsei University, Seoul, Korea.
Email: {jjmm1000, khy93, hsb1531, dynamics, csyong}@yonsei.ac.kr
†Electronics and Telecommunications Research Institute (ETRI), Daejeon, Korea
Email: {kimsk0729,skback}@etri.re.kr

***Abstract*—For millimeter wave (mmWave) massive multiple-input-multiple-output (MIMO) Xhaul systems, an initial beam search technique based on the maximum value of the codebook multiplied by the channel correlation matrix is proposed. Simulation results show the proposed initial beam selection scheme reduces complexity by more than 95% and improves up to 24% gain in terms of achievable rate compared with the conventional turbo-like tabu beam search algorithm with a random initial beam selection.**

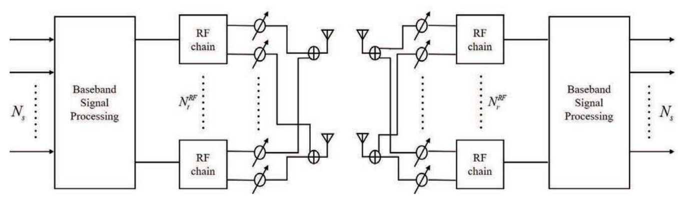

Fig. 1. Block diagram of mmWave MIMO system.

I. Introduction

The exponential growth of the fifth-generation (5G) wireless communication is expected in order to support a lot of devices and high data traffics [1]. Therefore, evolution of fronthaul and backhaul between the radio access network and packet core is necessary. Recently millimeter wave (mmWave) Xhaul which integrates fronthaul and backhaul using the mmWave in wireless communication systems has been considered as a promising solution [2][3]. However, path loss is one of the major problems in mmWave systems. To solve this problem, mmWave systems use massive multiple-input-multiple-output(MIMO) systems which use large antenna arrays to combat path loss [4].

In massive MIMO systems, a beamforming (including transmit precoding and receiving combining) technique is required [5]. mmWave Xhaul networks with massive MIMO systems usually use codebook-based beamforming techniques [6]. The optimal codebook-based beamforming scheme is exhaustive beam search method [7]. However, the exhaustive beam search method is too high complex to use in practical. Therefore, many low-complexity beam search schemes have been studied [8][9].

The initial beam selection is important for the conventional beam search scheme using tabu search algorithm [10][11]. In this paper, we introduce how to select an initial beam of tabu search algorithm using channel correlation matrix. To select the initial beam, we first obtain the modified codebook by multiplying channel correlation matrix to existing codebook. Then, a codebook vector which has the maximum power in the modified codebook is selected as the initial beam for the conventional beam search scheme using tabu search algorithm in order to reduce the complexity and improve the performance.

The rest of the paper is organized as follows. Section II presents the system model that describes the Xhaul network, massive MIMO systems and channel model considered in this paper. Section III explains the conventional turbo-liked tabu beam search algorithm briefly and introduces the proposed scheme. Section IV presents the simulation results. Finally, Section V concludes this paper.

Notation: $\mathbf{A}$ is a matrix, $\mathbf{a}$ is a vector and a is a scalar. $\mathbf{A}_{i,j}$ is the i th row and j th column element. $\mathbf{I}_N$ is the $N \times N$ identity matrix. $(\cdot)^{-1}$, $(\cdot)^T$, $(\cdot)^H$, $E(\cdot)$, and $det(\cdot)$ denote inversion, transpose, conjugate transpose, expectation, and determinant of a matrix, respectively. $(\mathbf{A})_F$ denote the Frobenius norm of matrix $\mathbf{A}$.

II. System Model

We consider the communication links between two Xhaul units. As shown in Fig. 1, the transmit Xhaul unit (transmitter) employs M_t antennas and N_t^{RF} RF chains to simultaneously transmit N_s data streams to the receive Xhaul unit (receiver) with N_r antennas and N_r^{RF} RF chains. To fully achieving the spatial multiplexing gain, we assume $N_t^{RF} = N_r^{RF} = N_s$ [12]. Under the narrowband block fading massive MIMO channel [12], the received signal vector $\mathbf{y}$ at the receiver can be presented as $\mathbf{y} = \sqrt{\rho}\mathbf{C}_A^H\mathbf{H}\mathbf{P}_A\mathbf{s} + \mathbf{C}_A^H\mathbf{n}$, where $\mathbf{s}$ is the $N_s \times 1$ data streams with $\mathrm{E}[\mathbf{s}\mathbf{s}^H] = 1$. ρ denotes the transmit power and $\mathbf{n} \sim \mathcal{CN}(\mathbf{0}, \sigma^2\mathbf{I}_{N_r})$ is the independent and identically distributed (i.i.d) additive white Gaussian vector. $\mathbf{P}_A$ and $\mathbf{C}_A$ are the $N_t \times N_s$ analog precoding matrix and the $N_r \times N_s$ analog combining matrix, respectively. Since $\mathbf{P}_A$ and $\mathbf{C}_A$ are the analog beamforming matrices [13], all elements should be satisfied with $\left|p_{i,j}^A\right| = 1/N_t$ and $\left|c_{i,j}^A\right| = 1/N_r$, where i and j denote the indexes of the row and column, respectively.

Considering Saleh-Valenzuela channel model [12], a $N_t \times N_r$ channel matrix $\mathbf{H}$ can be expressed as $\mathbf{H} = \sqrt{\frac{N_t N_r}{L}} \sum_{l=1}^{L} \alpha_l \mathbf{f}_r\left(\phi_l^r\right) \mathbf{f}_t^H\left(\phi_l^t\right)$, where L is the number of scatters and $\alpha_l \sim \mathcal{CN}(0,1)$ is the complex gain of lth path. ϕ_l^t and ϕ_l^r are the angle of departures (AoDs) and angle of arrivals (AoAs) of the lth path, respectively. The vectors $\mathbf{f}_t(\phi_l^t)$ and $\mathbf{f}_r(\phi_l^r)$ are the normalized transmit and receive array response vectors respectively. According to [14], the array response vector $\mathbf{f}\left(\phi\right)$ for an N-element uniform linear array (ULA) is given by

$$\mathbf{f}\left(\phi\right) = \frac{1}{\sqrt{N}}\left[1, e^{jkd\sin(\phi)}, \ldots, e^{j(N-1)kd\sin(\phi)}\right]^T, \qquad (1)$$

where $k = \frac{2\pi}{\lambda}$ and d is antenna spacing.

In this paper, we use codebook-based beamforming. Let $\mathbf{F}$ and $\mathbf{W}$ are the codebooks for analog precoding and combining matrices, respectively. Using (1), the analog precoding and combining matrices $\mathbf{P}_A$ and $\mathbf{C}_A$ are represented as

$$\mathbf{P}_A = \left[\mathbf{f}_t\left(\bar{\phi}_1^t\right), \mathbf{f}_t\left(\bar{\phi}_2^t\right), \ldots, \mathbf{f}_t\left(\bar{\phi}_{N_t^{RF}}^t\right)\right],$$
$$\mathbf{C}_A = \left[\mathbf{f}_r\left(\bar{\phi}_1^r\right), \mathbf{f}_r\left(\bar{\phi}_2^r\right), \ldots, \mathbf{f}_r\left(\bar{\phi}_{N_r^{RF}}^r\right)\right],$$

respectively, where $\bar{\phi}_i^t$ is the quantized AoD for i th RF chain ($i = 1, ..., N_t^{RF}$) and $\bar{\phi}_j^r$ is the quantized AoA for j th RF chain ($j = 1, ..., N_r^{RF}$). The number of bits for codebooks, $\mathbf{F}$ and $\mathbf{W}$, as B_t and B_r, respectively. Then, transmitter and receiver have $\left(2^{B_t}\right)^{N_{RF}^t}$ and $\left(2^{B_r}\right)^{N_{RF}^r}$ possible candidates, respectively. By the joint search for the codebooks, $\mathbf{F}$ and $\mathbf{W}$, the optimal beamforming pair is selected with the maximum achievable rate as

$$R = \max_{\mathbf{P}_A \in \mathbf{F}, \mathbf{C}_A \in \mathbf{W}} \log_2\left|\mathbf{I}_{N_S} + \frac{\rho}{N_s}\mathbf{R}_n^{-1}\mathbf{C}_A^H\mathbf{H}\mathbf{P}_A^H\mathbf{P}_A\mathbf{H}^H\mathbf{C}_A\right|, \qquad (2)$$

where $\mathbf{R}_n$ is the covariance matrix of noise after processing the analog combining matrix [12].

III. Conventional Turbo-like Tabu Beam Search Algorithm and Proposed Initial Beam Selection Scheme

In this section, we introduce the conventional turbo-like tabu beam search algorithm [11] and the proposed initial beam selection scheme.

A. Turbo-like tabu beam search algorithm

The turbo-like tabu beam search algorithm [11] consists of two loops. The inner loop is a tabu search algorithm, that is transmitter and receiver search beamforming matrices using the tabu beam search algorithm. The outer loop is a turbo-like joint search. During the turbo-like joint search, transmitter and receiver search a beam pair jointly based on the beamforming matrices resulting from the tabu beam search algorithm. The turbo-like tabu beam search algorithm can be operated as follows.

1) Neighborhood Definition: First, the neighborhood set of the initial beam should be defined in order to select the analog beamforming matrices. For example, when $N_{RF}^t = 1$, $B_t = 2$, and an initial beam at transmitter is $\mathbf{P}_A = \mathbf{f}_t(3\phi/2)$, the neighborhood set is $[\mathbf{f}_t(2\phi/2), \mathbf{f}_t(4\phi/2)]$.

2) Achievable Rate Computation: After defining the neighborhood set of the initial beam, the transmitter (receiver) computes achievable rates of all the possible combinations in the neighborhood set by using (2).

3) Beam Update: Using the obtained achievable rate, transmitter (receiver) selects the beamforming matrix having the highest achievable rate as a candidate beam. Then we compare the candidate beam with the selected beam. If the candidate beam has the higher rates than the selected beam, the candidate beam becomes the selected beam. If not, the selected beam is maintained. After the beam update is done, we return to 1). The processes from 1) to 3) repeat until the tabu iterations reach the defined maximum iteration or the selected beam does not change during the defined maximum update period.

4) Turbo-Like Joint Search: After the tabu beam search process from 1) to 3) (i.e., inner loop), transmitter (receiver) sends the selected beam to the receiver (transmitter) to search the optimal beam using the tabu beam search algorithm. Then the transmitter and receiver repeat this procedure until the defined turbo iteration.

B. Proposed Initial Beam Selection Scheme

In this subsection, the proposed initial beam selection scheme is presented. To select an initial beam, we multiply channel correlation matrix to the existing codebook and search the best beam pair. By a kronecker MIMO channel model [15], a channel matrix $\mathbf{H}$ can be expressed as

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{H}_w\mathbf{R}_t^{1/2}, \qquad (3)$$

where every entries of $\mathbf{H}_w$ is an i.i.d complex Gaussian random variable with zero mean and unit variance and $\mathbf{R}_t^{1/2}$ and $\mathbf{R}_r^{1/2}$ denote channel correlation matrices at the transmitter and receiver, respectively. Based on the channel correlation matrices $\mathbf{R}_t^{1/2}$ and $\mathbf{R}_r^{1/2}$, we can modify the existing codebooks as

$$\begin{aligned}\mathbf{F}' &= \mathbf{R}_t^{1/2}\mathbf{F}, \\ \mathbf{W}' &= \mathbf{R}_r^{1/2}\mathbf{W},\end{aligned} \qquad (4)$$

respectively, where $\mathbf{F}$ and $\mathbf{W}$ denote the existing codebooks. As shown in Fig. 2, a modified codebook can have skewed magnitudes and directions based on the channel correlation matrix. Based on the modified codebook $\mathbf{F}'$ and $\mathbf{W}'$, we propose a multiple initial beam selection scheme in order to choose better beam vectors. At the first beam selection, the transmitter and receiver choose N_t^{RF} and N_r^{RF} beam vectors in order of the power in $\mathbf{F}'$ and $\mathbf{W}'$, respectively. Then, at

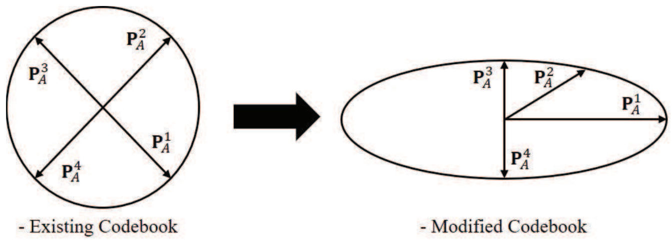

Fig. 2. Modified codebook using channel correlation matrix for proposed scheme.

the next beam selection, the initial beam selection can be performed by choosing N_t^{RF} and N_r^{RF} beam vectors except the previous selected beam.

C. Complexity Analysis

In this subsection, we analyze the complexity of the proposed scheme and compare with that of the conventional turbo-like tabu beam search algorithm. We also consider the full-search algorithm (i.e., exhaustive search) as in [7].

The complexity of the full-search algorithm C_{FS} can be expressed as

$$C_{FS} = \left(2^{B_t}\right)^{N_t^{RF}} \times \left(2^{B_r}\right)^{N_r^{RF}}. \tag{5}$$

As shown in (5), the complexity of the full-search algorithm depends on the codebook bit. In contrast, the complexity of the conventional tabu beam search algorithm does not depend on the codebook bit since the tabu search compares beams in the neighborhood set. The complexity of the conventional turbo-like tabu beam search algorithm C_{TS} can be expressed as

$$C_{TS} = \left(2N_t^{RF} \cdot T + 2N_r^{RF} \cdot T\right) MK, \tag{6}$$

where T, M, and K denote tabu beam search iteration, number of joint search iteration, and number of initial beam selection of conventional turbo-like tabu beam search algorithm, respectively. The proposed scheme requires the $N_t + N_r$ extra computations for an initial beam selection. The complexity of proposed scheme C_{PS} can be expressed as

$$C_{PS} = N_t + N_r + \left(2N_t^{RF} \cdot T + 2N_r^{RF} \cdot T\right) MK. \tag{7}$$

Using the proposed initial beam selection scheme, the beam search algorithm converges faster than the random initial beam selection method. To compare the complexity among three beam search algorithms as aforementioned, we consider $N_t^{RF} = N_r^{RF} = N_s = 2$ and $N_t = N_r = 64$ and the simulation parameters related to tabu beam search in Table I. In Table I, max-length denotes maximum update period.

The results of the complexity comparison can be shown in Table II. For the case of $B_t = B_r = 4$, the full search algorithm and the conventional turbo-like tabu beam search algorithm have the almost same complexity. However, the proposed scheme has only 5% complexity of the conventional turbo-like tabu beam search algorithm. As the codebook bit

TABLE I
SIMULATION PARAMETERS RELATED TO TABU SEARCH

	Conventional turbo-like tabu beam search algorithm [11]	Proposed scheme
Codebook bit	4bit/5bit/6bit	4bit/5bit/6bit
T	400/800/2500	100/200/600
max-length	100/200/600	50/100/200
K	4	2
M	5	2

TABLE II
COMPLEXITY COMPARISON

	Full-search algorithm [7]	Conventional turbo-like TS algorithm [11]	Proposed scheme (PS)	Complexity ratio(PS/TS)
4bit	6.5×10^4	6.4×10^4	3.2×10^3	5%
5bit	1×10^6	1.3×10^5	6.4×10^3	4.9%
6bit	1.7×10^7	4×10^5	1.9×10^3	4.7%

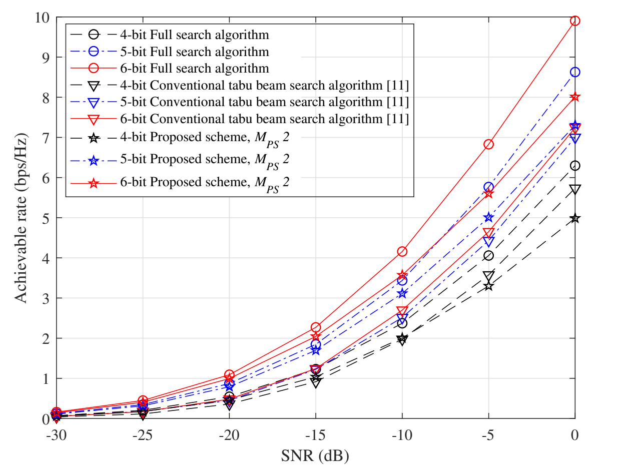

Fig. 3. Achievable rate of the full-search algorithm, the conventional tabu beam search algorithm [11], and the proposed scheme for $N_t = N_r = 16$ with $N_t^{RF} = N_r^{RF} = N_s = 2$.

becomes larger, the complexity difference between the conventional turbo-like tabu beam search algorithm and full-search algorithm increases. However, the complexity ratio between the proposed scheme and the conventional turbo-like tabu beam search algorithm (TS) becomes lower.

IV. SIMULATION RESULTS

In this section, we evaluate the achievable rates of the proposed initial beam selection scheme, the full-search algorithm and the conventional turbo-like tabu beam search algorithm in the Saleh-Valenzuela channel model [12]. We assume that AoAs and AoDs are uniformly distributed over $[0, \pi]$ and the carrier frequency is 28 GHz. The simulation parameters related to the tabu beam search algorithm are shown in Table I.

Fig. 3 shows the achievable rates of the full-search algorithm, the conventional turbo-like tabu search algorithm, and the proposed scheme for $N_t = N_r = 16$ with

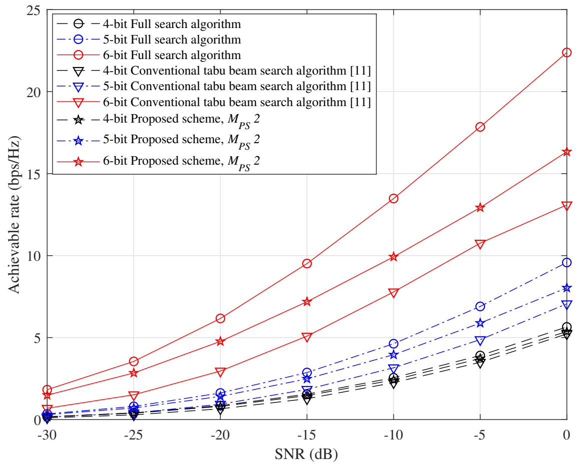

Fig. 4. Achievable rate of the full-search algorithm, the conventional tabu beam search algorithm [11], and the proposed scheme for $N_t = N_r = 64$ with $N_t^{RF} = N_r^{RF} = N_s = 2$.

$N_t^{RF} = N_r^{RF} = N_s = 2$. The conventional turbo-like tabu beam search algorithm executes M times initial beam selection to guarantee reliable performance since the initial beam selection is randomly selected. For the case of $B_t = B_r = 4$, the proposed scheme has the lower achievable rates than the conventional turbo-like tabu beam search algorithm. However, for $B_t = B_r = 5$ and $B_t = B_r = 6$, the proposed scheme outperforms the conventional turbo-like tabu beam search algorithm. We can also observe that the proposed scheme for $B_t = B_r = 6$ with only 0.2% complexity shows similar performances to the full-search algorithm for $B_t = B_r = 5$.

Fig. 4 shows the achievable rates of the full-search algorithm, the conventional turbo-like tabu beam search algorithm, and the proposed scheme for $N_t = N_r = 64$ with $N_t^{RF} = N_r^{RF} = N_s = 2$. We can observe the similar trends as in Fig. 3. As shown in Fig. 4, the proposed scheme can achieve the 24% improved achievable rates at 0 dB SNR with 95.3% reduced complexity compared to the conventional turbo-like tabu beam search algorithm with $B_t = B_r = 6$. According to the simulation results, we can conclude that the proposed initial beam selection scheme achieves both low complexity and achievable rate improvement over the conventional turbo-like tabu beam search algorithm.

V. Conclusion

In this paper, we proposed an initial beam selection scheme for the tabu beam search algorithm using channel correlation matrix. The achievable rates and the complexity of the proposed scheme are evaluated. Simulation results show that the proposed scheme can achieve the reduced complexity by up to more than 95% and up to 24% improvement of achievable rate compared with the conventional turbo-like beam search algorithm. Therefore the proposed initial beam selection scheme converges compared with conventional turbo-like tabu beam search algorithm to the optimal performance.

Acknowledgment

This work was partly supported by Institute for Information & communications Technology Promotion(IITP) grant funded by the Korea government(MSIT) (No.2014-0-00282,Develop- ment of 5G Mobile Communication Technologies for Hyper- connected smart services) and Institute for Information& com- munications Technology Promotion(IITP) grant funded by the Korea government(MSIT)(No.2016-0-00181,Developmenton the core technologies of transmission, modulation and coding with low-power and low-complexity for massive connectivity in the IoT environment)

References

[1] Recommendation ITU-R M.2083: IMT Vision - "Framework and overall objectives of the future development of IMT for 2020 and beyond", Sep. 2015.

[2] A. D. L. Oliva, X. C. Perez, A. Azcorra, A. D. Giglio, F. Cavaliere, D. Tiegelbekkers, J. Lessmann, T. Haustein, A. Mourad, and P. Iovanna, "Xhaul: toward an integrated fronthaul/backhaul architecture in 5G networks," *IEEE Wireless Commun.*, vol. 22, no. 5, pp. 32-40, Oct. 2015.

[3] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, "A survey of millimeter wave (mmWave) communications for 5G: Opportunities and challenges," *arXiv preprint arXiv:1502.07228*, Feb. 2015.

[4] Z. PiandF. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Comm. Mag.*, vol. 49, no. 6, pp. 101–107, 2011.

[5] C. Sheldon, M. Seo, E. Torkildson, M. Rodwell, and U. Madhow, "Four-channel spatial multiplexing over a millimeterwave line-of-sight link," *IEEE Int. Microwave Symposium Digest*, pp. 389–392, Jun. 2009.

[6] W. Roh et al., "Millimeter-wave beamforming as an enabling technology for 5G cellular communications: Theoretical feasibility and prototype results," *IEEECommun. Mag.*, vol. 52, no. 2, pp. 106–113, Feb. 2014.

[7] T. Kim et al., "Tens of Gbps support with mmWave beamforming systems for next generation communications," *in Proc. IEEE GLOBECOM*, Dec. 2013, pp. 3685–3690.

[8] M. S. Rahman and K. Josiam, "Low complexity RF beam search algorithms for millimeter-wave systems millimeter-wave systems," *in Proc. IEEE Global Telecommun. Conf. (GLOBECOM)*, 2014, pp. 3815–3820.

[9] W. Yuan, S. M. D. Armour, and A. Doufexi, "An Efficient and Low-complexity Beam Training Technique for mmWave Communication," *in PIMRC,* 2015

[10] Lemasri Piniganti, "A survey of Tabu Search in Combinatorial Optimization," *University of Nevada*, Las vegas, United States, May. 2014.

[11] Xinyu Gao, Linglong Dai, Chau Yuen, and Zhaocheng Wang, "Turbo-like beamforming based on tabu search algorithm for millimeter-wave massive MIMO systems,"*IEEE Trans. Veh. Technol.*, vol. 65, no.7, pp. 5731-5737, Jul. 2016.

[12] O. El Ayach, S. Rajagopal, S. Abu-Surra, Z. Pi, and R. Heath, "Spatially sparse precoding in millimeter wave MIMO systems," *IEEE Trans. Wireless Commun.*, vol. 13, no. 3, pp. 1499–1513, Mar. 2014.

[13] M. M. Molu, P. Xiao, M. Khalily, K. Cumanan, L. Zhang , and R. Tafazolli, "Low-Complexity and Robust Hybrid Beamforming Design for Multi-Antenna Communication Systems" *IEEE Trans. Wireless Commun.*, vol. 17, no. 3, pp. 1445–1459, Mar. 2018.

[14] C. Balanis, *Antenna theory*. Wiley New York, 1997.

[15] D. Gesbert et al., "Outdoor MIMO wireless channels: models and performance prediction," *IEEE Trans. Commun.*, vol. 50, no. 12, pp. 1926-1934, Dec. 2002.