Design and Development of Novel Hybrid Precoder for Millimeter-Wave MIMO System

Srinivas K, T.Srinivasulu[1]

[1]Department of ECE, Kakatiya University, India

Abstract: Power consumption and hardware cost reduction with the use of hybrid beamforming in large-scale millimeter wave MIMO systems. The large dimensional analog precoding integrates with the hybrid beamforming based on the phase shifters including digital precoding with lower dimensionality. The reduction of Euclidean distance between the hybrid precoder and fully digital is the major problem to overcome the minimization of resultant spectral efficiency. The issue formulates as a fully digital precoder's matrix factorization problem based on the analog RF precoder matrix and the digital baseband precoder matrix. An additional element-wise unit modulus constraint is imposed by the phase shifters on the analog RF precoder matrix. The traditional methods have a problem of performance loss in spectral efficiency. In the processing time and iteration, high complexities result in optimization algorithms. In this paper, a novel low complexity algorithm proposes which maximizes the spectral efficiency and reduces the computational processing time.

Keywords: Hybrid beamforming, MIMO, Hybrid precoder design, millimeter-wave..

1. Introduction

Based on the extensive growth of mobile communication data volume and mobile communication equipment with the continuous increase in energy consumption, people are concerned about the system capacity of 5G mobile communication systems. It's required to achieve energy efficiency and quantity [1]. The existing systems of low-frequency mobile communication have an issue of satisfying the increasing demand of users for data services owing to the scarcity in the spectrum resources lack of restrictions. So, researchers and engineers have focused on improving the underutilized millimeter-wave frequencies [2]. Here, millimeter-wave relates to the frequency spectrum electromagnetic waves that range from 30 to 300 GHz and wavelength ranging from 1 to 10 mm. The system's transmission rate can increase as the bandwidth can reach up to 10GHz. For 5G communication systems, it regards as one of the candidate spectrums [3]. However, Millimeter waves are easily affected by oxygen and rain, leading to large propagation loss and making millimeter-wave communication face huge challenges. For obtaining an array gain of a larger antenna for compensating the meter wave channel's path loss, the milli-mater wave frequencies can be useful for deployment of a large number of antennas using the precoding technology because the wavelength is small. Hence, the quality of channel transmission improves. One of the 5G emerging technologies includes the millimeter-wave and large-scale multiple-input multiple-output (MIMO) technology [4].

In the transmission process of the wireless communication system, radio frequency (RF) link (including digital-to-analog converter, mixer, and power amplifier converter, etc.) after up-converting and modulating the pre-processed baseband signal through the antenna line to launch. The technology of digital precoding is used in conventional MIMO systems for pre-processing the transmitted signal in the baseband part to eliminate the Interference for achieving the improved performance of a system [5]. However, on the digital precoding side, each antenna needs to correspond to an RF link. As the system increase in the number of end antennas will inevitably lead to system implementation costs and energy consumption. The substantial increase in the application of mm-Wave massive MIMO technology has brought obstacles to hinder. For restricting this problem, a method was proposed by some scholars for simulating precoding cases [6,7]. For controlling the transmitted signal by each antenna phase, analog precoding is used for low-cost and low-power phase shifters, unlike digital precoding. The analog precoding's implementation cost of energy consumption is lower usually compared to the digital precoding. It's different for changing the phase bit and signal amplitude in the digital precoding. The signal phase can change only by analog precoding. So, the performance degrades than the digital precoding [8].

2. Literature Survey

In recent years, some scholars have integrated digital precoding and analog precoding advantages, a hybrid precoding scheme combining analog and digital is proposed. A high-dimensional modulus quasi-precoder and a low-dimensional digital precoder contain in the mixed precoder. Through a small number of RF links, they connect each other and the energy consumption and implementation cost of a system reduce. It achieves the better performance of a system. Reference [9] considers the spatial sparsity of millimeter-wave channels on this basis, the design issues of the base station precoder and the user side combiner are considered for the problem of sparse signal reconstruction, a method based on orthogonal matching is proposed (OMP) hybrid precoding algorithm, the performance of the algorithm can be close to that of the all-digital precoding algorithm. In reference Xian [10] fully considers that the analog precoder is restricted by circuit conditions and the base station on the basis that the terminal can only obtain part of the channel information, an iterative-based hybrid precoding algorithm. In a single-user millimeter-wave channel, the algorithm's performance can reach the performance near to the conventional all-digital precoding algorithm. In reference [11] proposed a low-complexity hybrid using semi-unitary optimal precoder. The precoding and merging scheme can effectively reduce the popular search space of the array compared with the proposed algorithm in reference [9], this scheme has lower calculation complexity. Reference [12] derives that the system needs to achieve optimal performance lower bound of the number of RF links. However, in the hybrid mentioned in reference [9-12], the precoding scheme only considers single-user MIMO systems and does not consider the multi-use scene. For multi-user scenarios, reference [13] considers the total power based on rate limitation, a method that can maximize the hybrid precoding algorithm with a small signal-to-interference and noise ratio, the average signal that the algorithm can achieve interference-to-noise ratio is very close or even better than the traditional iterative algorithm, but the algorithm does nota restrict that the analog precoding matrix's each element should meet the constant modulus condition. Reference [14] fully considers the asymptotic orthogonality of massive MIMO system channels features, a two-level structure of low complexity hybrid precoding algorithm proposes, where the analog part is used to provide greater power gain, and the digital part is used to eliminate interference between multiple users. Through this design, the algorithm can achieve better performance. However, this scheme only considers the aspect of single-antenna users. And because it did not consider the analog and digital parts of the hybrid precoding optimization of points, the system performance of the algorithm needs to be improved.

Fulai Liu [15] has proposed an AMLSA algorithm using the principle of alternating minimization to achieve hybrid precoding for mmWave MIMO systems. The proposed algorithm's effectiveness proves by simulation results such as increased spectral efficiency to some extent, and reduced number of iterations slightly through the improved initialization procedure. Hiroyuki Kasai [16] has proposed a new algorithm of fast optimization to limit the performance loss of spectral efficiency. The proposed method shows superior performance in higher spectral efficiency and faster processing than the existing methods such as the low-complexity PE-AltMin algorithm and MO-AltMin algorithm. Xianghao Yu [17] has proposed and implemented a cost-effective hybrid precoder based on a small number of fixed phase shifters for millimeter-wave systems. For a low-complexity AltMin algorithm, a dynamic switch network adopts to improve the fully digital precoder's performance. For 5G mm-wave systems, the proposed technique ensures the achievement of the improved solution for hybrid precoders. Xianghao Yu and Khaled B. Letaief [18] have proposed alternating minimization algorithms with an innovative design methodology for the partially connected and fully connected structures of hybrid precoding. Their performance can achieve with the hybrid precoders when the number of data streams is higher than the number of RF chains. By improving a large number of RF chains relatively, both energy and spectral efficiencies can improve.

3. System Model

Figure 1 shows the shared array architecture of a millimeter-wave large-scale MIMO system. At the transmitting end, the number of transmitting antennas indicates as N_t, the number of RF links at the transmitting end is N_t^{RF}, the number of receiving antennas is N_r, the dataflow at the transmitting and receiving end is N_s, and the number of radiofrequency links at the receiving end is N_r^{RF}.

For ensuring the transmission of multiple data streams, $N_s \leq N_t^{RF} \leq N_t$ and $N_s \leq N_t^{RF} \leq N_r$must be satisfied. Under this hardware structure, the signal passes baseband precoder $F_{BB} \in \mathbb{C}^{N_t^{RF} \times N_s}$ and RF precoder $F_{RF} \in \mathbb{C}^{N_s \times N_t^{RF}}$.

The processing of t is transmitted to the channel

$H \in \mathbb{C}^{N_r \times N_t}$.

At the transmitting end the transmitted signal is

$$x = F_{RF}F_{BB}s \quad (1)$$

In the formula: $s = [s_1, s_2, \dots, s_{N_s}]^T$is the signal's data stream and $E[ss^H] = \frac{1}{N_s} I_{N_s}$; $x = [x_1, x_2, \dots, x_{N_t}]^T$ is the transmitting end radio signal.

After channel transmission, the receiving signal at the receiving end antenna is:

$$y = \sqrt{\rho} H F_{RF} F_{BB} s + n \quad (2)$$

Where: $n \in \mathbb{C}^{N_r}$ means that the mean of obedience is 0, and the covariance matrix is σ^2 , Gaussian white noise is I_{N_r}; $y = [y_1, y_2, \dots, y_{N_r}]^T$at receiver end signal; ρ represents the average received power; the channel moment array indicates by H, and it is $E[H||_F^2] = N_t N_r$. Use radio frequency combiner received signal $W_{BB} \in \mathbb{C}^{N_t^{RF} \times N_s}$ for further processing, the obtained connection receiving signal is

$$\hat{y} = \sqrt{\rho} W_{BB}^H W_{RF}^H H F_{RF} F_{BB} s + W_{BB}^H W_{RF}^H n \quad (3)$$

Where,$\hat{y} = [\hat{y}_1, \hat{y}_2, \dots, \hat{y}_{N_s}]^T$indicates the received signal at the receiver end. Since the implementation of F_{RF} uses the analog moving network, its element Sustained $\left(F_{RF}^{(i)} F_{RF}^{(i)H}\right)_{l,l} = 1/N_t$, $(.)_{l,l}$ represents the l[th] matrix Diagonal elements. Similarly, $\left(W_{RF}^{(i)} W_{RF}^{(i)H}\right)_{l,l} = 1/N_r$. Transmitter total power constraint is$[\![F_{RF}F_{BB}]\!]_F^2 = N_s$.

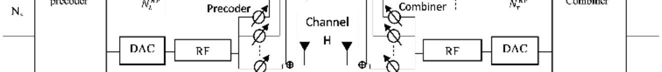
Taking into account the high path loss and spatial scarcity of millimeter-wave channels. The characteristics of sparse distribution, and the transceiver in a large-scale MIMO system The upper antenna array is tightly arranged, and the antenna elements are highly correlated. Due to the implementation of the Ray tracing model in the fading statistical channel, it is not being used. The propagation paths of N_{ray} contain in each cluster and the system's channel H in the millimeter-wave channel and it can describe as follows:

$$H = \sqrt{\frac{N_t N_r}{N_{cl} N_{ray}}} \sum_{i,l} \alpha_{i,l}\, a_r(\varphi_{il}^r)^H \quad (4)$$

Where: $\alpha_{i,l}$ represents the i[th] propagation path in the l[th] scattering cluster Gain factor, subject to mean 0 and variance $\sigma_{\alpha,i}^2$ complex Gaussian fraction of I Cloth, and satisfies $\sum_{i=1}^{N_{cl}} \sigma_{\alpha,i}^2 \Gamma$, γ needs to satisfy $E[||H||_F^2] = N_t N_r$; φ_{il}^r is the angle of arrival (angle of arrival, AOA), and for The i[th] scattering cluster, φ_{il}^r at φ_i^r Randomly distributed on i; $\varphi_{il}^r$is the departure angle (Angle of departure, AOD), and for the i[th] scattering cluster, φ_{il}^r At φ_i^r random distribution on i, we select the Laplace distribution as Random distribution method; at $a_t(\varphi_{il}^r)$ and $a_r(\varphi_{il}^r)$ respectively represent launch Array response vector of the end and the receiving end.

According to the antenna arrangement in the array, the type of antenna array models can be combined into various styles. A design of a uniform antenna array is considered in the millimeter-wave large-scale MIMO system. Uniform planar arrays and uniform linear arrays include in the common uniform antenna arrays. The uniform linear array uses for analysis. The array response vector can express below by assuming the y-axis has N antennas for a uniform linear array:

$$a(\varphi) = \sqrt{\frac{1}{N}} \left[e^{jkd\sin(\varphi)}, e^{j2kd\sin(\varphi)}, \dots, e^{j(n-1)kd\sin(\varphi)}\right]^T \quad (5)$$



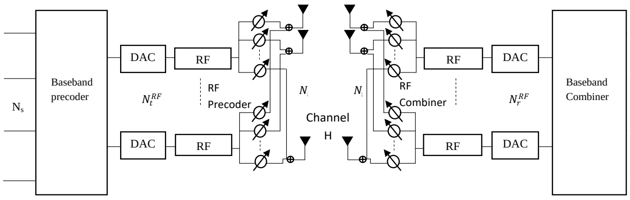


Figure 1: Block diagram of Hybrid precoder in millimeter-wave MIMO

In the formula: φ ∈[0, 2π], k = 2π/λ, and d is the antenna element spacing. Through the channel estimation, the channel state information (CSI) can know in the actual system. The system frequency spectral efficiency is evaluated by assuming the transceiver side knows the CSI for precoding:

$$R = \log_2 \left| I_{N_2} + \frac{\rho}{N_2} R_n^{-1} W_{BB}^H W_{RF}^H H F_{RF} F_{BB} F_{BB}^F F_{RF}^F H^H W_{RF} W_{BB} \right| \quad (6)$$

Where $R_n = \sigma^2 W_{BB}^H W_{RF}^H W_{RF} W_{BB}$ is processed by the receiving end noise covariance matrix. In literature [9] will maximize the spectrum efficiency approximation equivalent to minimize the hybrid precoding matrix and the Euclidean distance of all-digital precoding matrix. The problem of precoding design can be written as follows:

$$F_{RF}^{opt}, F_{BB}^{opt} = \underset{F_{RF}, F_{BB}}{\operatorname{argmin}} \left\| F_{opt} - F_{RF} F_{BB} \right\|_F \quad (7)$$

Where, $F_{RF} \in \mathcal{F}_{RF}, \|F_{RF} F_{BB}\|_F^2 = N_s$

Where F_{opt} is the all-digital precoding matrix, which is the channel matrix H that has the first columns of the right singular matrix N_s. If it is satisfied, the problem of precoding design can express as $F_{RF} \in \mathcal{F}_{RF}$, F_{opt} is found in the mixed projection on the subspace formed by the $F_{RF}F_{BB}$ set of precoders. At the receiving end, the combiner's design method is the same.

4. Proposed Model

In millimeter-wave massive MIMO systems, a low-complexity Hybrid precoding method, which firstly sets the RF precoding calculation, and then iteratively updates the RF By performing singular value decomposition on the perfect all-
digital precoding matrix, construct an initial RF precoding matrix. From equation (7), the objective function $\left\| F_{opt} - F_{RF} F_{BB} \right\|_F$ represents the best full number euclidean distance between the precoding matrix F_{opt} and the actual hybrid precoding matrix $F_{RF} F_{BB}$ under restricted conditions. Assuming that the constant modulus limit of F_{RF} is ignored, for now, then the initial RF precoding matrix can pass the singular value of the optimal all-digital precoding matrix F_{opt} decompose to design, the singular value decomposition of F_{opt} is as follows:

$$F_{opt} = SVD^H \quad (8)$$

precoding matrix and digital precoding matrix. Where optimal matrix $F_{opt}$is the first N_s columns of the right singular matrix of the channel matrix, SV is $N_t \times N_s$full-rank matrix and RF precoding matrix is $N_t \times N_{RF}^t$.Therefore, to determine the initial RF precoding matrixF_{RF}, here $N_t \times (N_{RF}^t - N_s)$ dimensional matrixF_R, so that the phase of its elements obeys uniformity distributed on [0,2π]. At the same time, it is forced to limit its amplitude to$1/\sqrt{N_t}$, which meets RF pre-programming element constant modulus restriction of the code matrix. Combining formula (8), F_{opt} has the following equivalent means:

$$F_{opt} = [SV\ F_R] \begin{bmatrix} D^H \\ O \end{bmatrix} \quad (9)$$

According to equation (9), it can be seen that, under unlimited conditions, by performing odd different value decomposition can get two global optimal solutions:

$$F_{RF}^* = [SV\ F_R] \quad (10)$$

$$F_{BB}^* = [D\ O]^H \quad (11)$$

When considering the condition of RF constant mode limitation, due to F_{RF}^* medium SV is not a satisfied condition, then the SV part of the formula (10) is processed, the specific processing steps are as follows:

Step 1: Keep the phases of all elements in SV;
Step 2: Force the amplitude of all elements to be$1/\sqrt{N_t}$.

Let the SV processed by the above steps be denoted by G, namely [G F_R] as the initial RF precoding matrixF_{RF}. Observing the above process, we can see that G still contains the phase information of equation (10).

The residual vector produced by the biggest singular vector of the matrix is used to update the initial RF precoding moment array based on the F_{RF}design of the first RF precoding matrix. In each iteration, the first column of the initial RF precoding matrix will be eliminated, and the least-squares criterion used for determining the digital precoding matrix $F_{BB}$and the current residual matrixF_{res}, and then perform singular values on the residual matrix decompose and add the vector constructed by its largest left singular vector to the RF matrix in the last column of the initial matrix for the next iteration. After N_{RF}^t times generation, we get the updated RF precoding matrix. Finally, use least squares again multiply the criteria to get the digital precoding matrix, and standardize it. The overall steps are as follows:

Step 1: $k = 1$;

Step 2: Eliminate the first column in the precoding matrixF_{RF} :$F_{RF}(:,1) = [\ \ ]$;

Step 3: Use the least square criterion to get the corresponding digital precoding matrix:

$$F_{BB} = \left(F_{RF}^H F_{RF}\right)^{-1} F_{RF}^H F_{opt} = \operatorname{pinv}(F_{RF}) F_{opt};$$

Step 4: Calculate the residual matrix at this time$F_{res} = F_{opt} - F_{RF} F_{BB}$;

Step 5:Perform singular value decomposition on the resulting residual matrix: $F_{res} = USV^H$, where, U and V refer to the residual matrix's left and right singular matrices, respectively.

Step 6: A vector is formed by the largest left singular vector $U(:,1)$of the residual matrix amount $n = 1/\sqrt{N_t} e^{j\mathrm{angle}(U(:,1))}$;

Step 7: Let$F_{RF} = [F_{RF}\ n]$, Use it as the initial RF for the next iteration precoding matrix.

Step 8: $k = k + 1$, in case, $k \neq N_{RF}^t + 1$, Return to step 2, otherwise to Step 9.

Step 9: After determining theF_{RF}, use the least-squares criterion to find the corresponding digital precoding matrix$F_{BB} = \operatorname{pinv}(F_{RF}) F_{opt}$, and standardize it, to meet the transmit power limit, namely:

$$F_{BB} = \frac{\sqrt{N_s} F_{BB}}{\|F_{RF} F_{BB}\|_F} \quad (12)$$

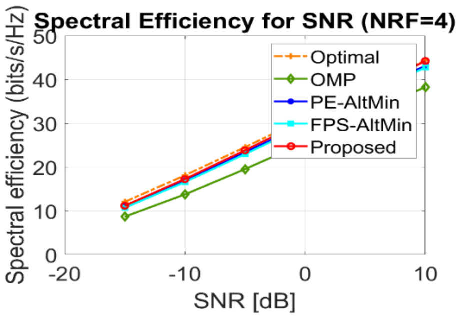
According to the above steps, we mainly use the largest left singular vector of the residual matrix to update the initial RF matrix based on the constant modulus vector constructed by the quantity. Among them, the construction of the constant modulus vector contains the information of the residual matrix. Therefore, the vector and the residual matrix correlation are great. In each iteration, use the constant modulus vector to update the RF matrix will make the designed hybrid precoding matrix approach the optimal matrix. Therefore, the performance of the system will also improve.

5. Simulation analysis

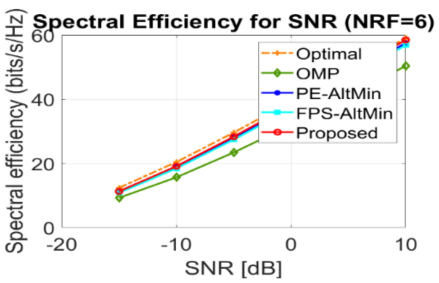
The proposed method of hybrid precoding's performance simulates by using the true parameters: N_t= 144 and 256 antennas at the transmitter, N_r = 36 and 64 at the receiver Antenna; the number of clusters N_{cl}= 5, the number of paths in each cluster is N_{ray}=10, and each cluster the average power of the cluster is $\sigma_{i,l}^2 = 1$. Let us assume that both AOD and AOA of azimuth obey Laplace distribution, where the cluster angle obeys a uniform distribution on $[0,2\pi]$, and the angle degree extension is set to 10°. The proposed algorithm was tested in a narrow band and compared with hybrid precoding schemes.

Simulation 1: Under the same conditions of N_{RF} and data streams, the proposed method is compared with all hybrid precoding methods such as optimal method, OMP, PE-Altmin, and FPS-Altmin [9-17].

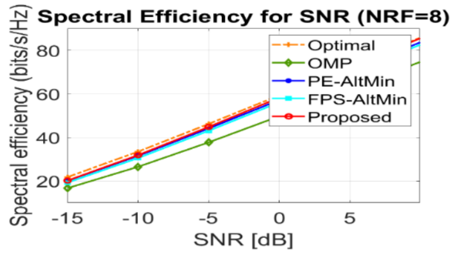
Figure 2 shown in $N_{RF}^t = N_{RF}^r = N_s = \{4,6,8\}$ and $(N_t, N_r) = (144, 36)$conditions, different pre-spectrum efficiency achieved by the coding scheme varies with the SNR. Similarly, figure 3 shown in $N_{RF}^t = N_{RF}^r = N_s = \{4,6,8\}$ and $(N_t, N_r) = (256, 64)$conditions, different pre-spectrum efficiency achieved by the coding scheme varies with the SNR From figure 2 and 3, it can be seen that under the same condition that the number of radiofrequency chains N_{RF} and the number of data streams N_s, the relative comparison with the technique of hybrid precoding based on Optimal, Altmin and OMP algorithms in references [9],[15-17], its performance can be closer to the scheme of optimal all-digital precoding. By using the OMP algorithm When N_{RF}=N_s, the performance of the hybrid precoding method is poor. Considering the complexity factor indicates that the method proposed method is not only less complex but also the performance is relatively good.



a) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 4$

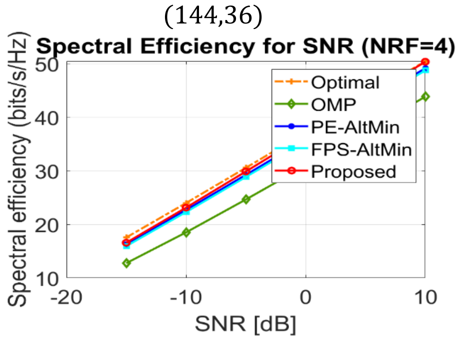


b) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 6$

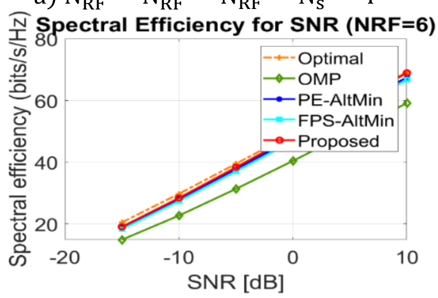


c) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 8$

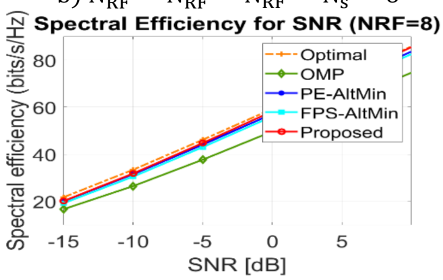
Figure 2: Spectral Efficiency when the number of data streams is equal to the number of RF links $(N_t, N_r) = (144,36)$



a) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 4$



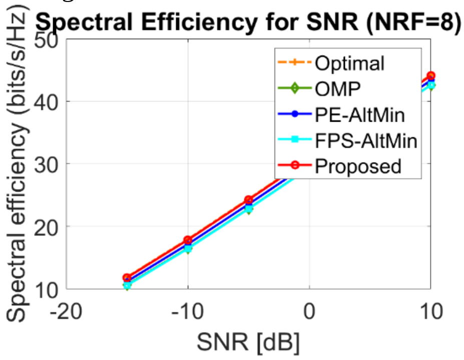
b) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 6$



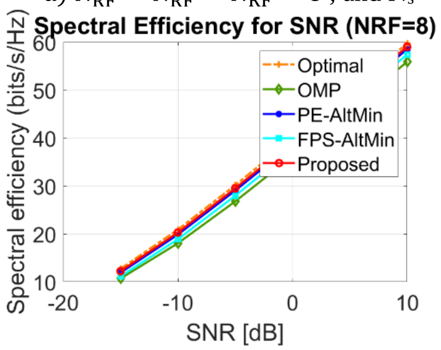
c) $N_{RF}^t = N_{RF}^r = N_{RF} = N_s = 8$

Figure 3: Spectral Efficiency when the number of data streams is equal to the number of RF links$(N_t, N_r) = (256, 64)$

Simulation 2: When the N_{RF} is fixed, the proposed method is compared with all hybrid precoding methods such as optimal method, OMP, PE-Altmin, and FPS-Altmin [9, 15, 16, 17]. Figure 4 shows in $N_{RF}^t = N_{RF}^r = N_{RF} = 8$, the data streams are respectively N_s = $\{4,6,8\}$ under the conditions$(N_t, N_r) = (144,36)$, the spectral efficiency obtained by different precoding schemes increases with the SNR. Similarly $N_{RF}^t = N_{RF}^r = N_{RF} = 8$, the data streams are respectively $N_s = \{4,6,8\}$ under the conditions $(N_t, N_r) = (256, 64)$, the spectral efficiency obtained by different precoding schemes increases with the SNR. It can be seen from Figures 4 and 5 when data flow is small, the performance of the combined precoding method and hybrid precoding method is almost close to the optimal all-digital precoding schemes using the OMP algorithm. But as the data flow increases the proposed hybrid pre-coding method is significantly better than the hybrid pre-coding based on OMP. This shows that when the data stream is large, the mixed pre-design of this method encoders have obvious advantages.

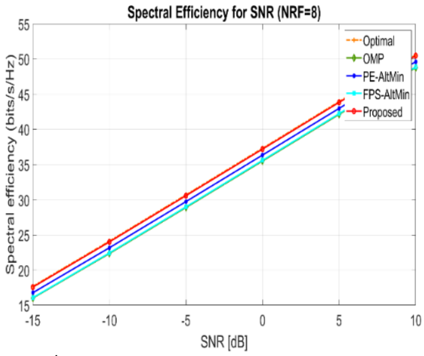


a) $N_{RF}^{t} = N_{RF}^{r} = N_{RF} = 8$, and N_s =4

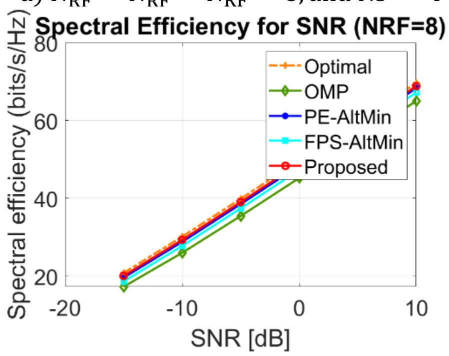


b) $N_{RF}^{t} = N_{RF}^{r} = N_{RF} = 8$ and Ns $= 6$

Figure 4: System performance of different data streams when the number of RF links is fixed$(N_t, N_r) = (144,36)$



a) $N_{RF}^{t} = N_{RF}^{r} = N_{RF} = 8,$ and Ns $= 4$

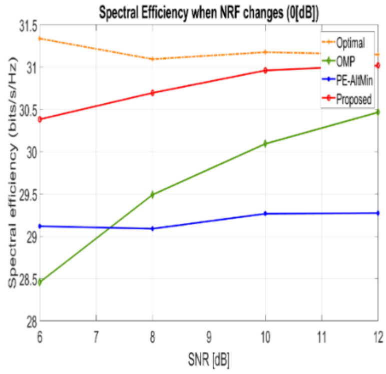


b) $N_{RF}^{t} = N_{RF}^{r} = N_{RF} = 8,$ and Ns $= 6$

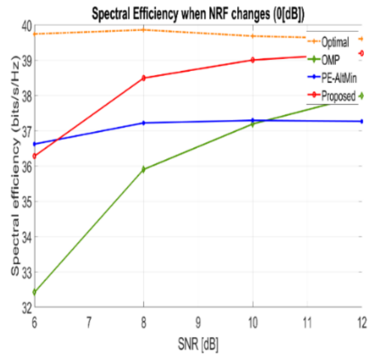
Figure 5: System performance of different data streams when the number of RF links is fixed $(N_t, N_r) = (256, 64)$

Simulation 3: SNR is fixed, the proposed method is compared with all hybrid precoding methods such as optimal method, OMP, PE-Altmin, and FPS-Altmin [9, 15, 16, 17] with performance comparison under different N_{RF}.

Figure 6 shows that when N_s = {4, 6} and SNR=0 dB, different precoding methods obtained spectrum efficiency varies with NRF. System performance is greatly by the number of RF links shown in Figure 6. By comparing with the hybrid precoding technique with the OMP algorithm when $N_{RF} \geq 2N_s$, the precoding method proposed in this paper encoding method, its performance has obvious advantages, specifically if the small number of data streams existed when the spectrum efficiency is nearer to the optimal all-digital precoding method



a) SNR=0 and N_s =4



b) SNR =0 and N_s =6

Figure 6: System performance of different data streams when SNR is fixed

In use, the greater the number of RF links, it means that after processing by the hybrid precoder system performance is better, but at the same time, the system cost and power consumption. Therefore, in the actual system, the system performance depends on several RF links.

6. Conclusion

Millimeter-wave massive MIMO system uses traditional all-digital precoding. A large number of RF links need to be used in the solution, which leads to more consumption of energy and implementation costs of a system. So, it's not beneficial for the millimeter-wave massive MIMO technology. Hybrid precoding with low-complexity proposes to restrict the issues of a hybrid precoding scheme for millimeter-wave large-scale MIMO systems. The proposed technique of hybrid precoding uses the most residual large left singular vector constructs the RF vector and updates RF through multiple iterations precoding matrix, so the complexity is relatively low. At the same time, this method does not require prior design candidate vector sets.

References

[1] Dr. Dalveer Kaur, Neeraj Kumar. "Dexterity for Channel Capacity Enhancement in MU-MIMO by Abrogatig Interference". *International Journal of Communication*

Networks and Information Security (IJCNIS), Vol. 11, No. 1, April 2019

[2] Wang T, Li G, Ding J, et al. "5G spectrum: is China ready", *IEEE Communications Magazine*, 53(7): pp. 58-65, 2015.

[3] Fang J, Li J C, Huang B, et al. "Review and prospect on the research of 5G spectrum", *Telecommunications Science*, 31(12): pp. 103-110, 2015

[4] Long B L, Lau V, Jorswieck E, et al. "Enabling 5G mobile wireless technologies", *EURASIP Journal on Wireless Communications and Networking*, pp.1-14, 2015.

[5] Larsson E.G, Edfors O, Tufvesson F, et al. "Massive MIMO for next-generation wireless systems", *IEEE Communications Magazine*, 52(2): 186-195, 2014.

[6] Chen L, Yang Y, Chen X, et al. "Multi-stage beamforming codebook for 60 GHz WPAN", *International ICST Conference on Communications & Networking*, Aug 17-19, 2011, Chengdu, China. New Jersey: IEEE Press, pp.361-365, 2011.

[7] Hur S, Kim T, Love D J, et al. "Millimeter wave beamforming for wireless backhaul and access in small cell networks", *IEEE Transactions on Communications*, vol.61(10): pp.4391-4403,2013.

[8] Sohrabi F and Yu W, "Hybrid digital and analog beamforming design for large-scale antenna arrays" *IEEE Journal of Selected Topics in Signal Processing*, 2016.

[9] Ayach O E, Rajagopal S, Abu-Surra S, et al. "Spatially sparse precoding in millimeter wave MIMO systems", *IEEE Transactions on Wireless Communications, vol.*13(3): pp.1499-1513, *2013*.

[10] Alkhateeb A, El Ayach O, Leus G, et al. "Hybrid precoding for millimeter wave cellular systems with partial channel knowledge", *Information Theory and Applications Workshop*, Feb 10-15, 2013, San Diego, California, USA. New Jersey: IEEE Press,pp: 1-5, 2013.

[11] Rusu C, Mendez-Rial R, Gonzalez-Prelcicy N, et al. "Low complexity hybrid sparse precoding and combining in millimeter wave MIMO systems" *IEEE International Conference on Communications*, June 8-12, 2015, Hangzhou, China. New Jersey: IEEE Press,pp.1340-1345, 2015.

[12] Zhang E and Huang C, "On achieving optimal rate of digital precoder by RF-baseband design for MIMO systems" *Vehicular Technology Conference*, Sept 14-17, 2014, Vancouver, BC, Canada. New Jersey: IEEE Press,pp: 1-5, 2014

[13] Li N, Wei Z, and Geng J, et al. "Multiuser hybrid beamforming for max-min SINR problem under 60 GHz wireless channel", *IEEE International Symposium on Personal, Indoor*, and Mobile Radio Communication, Sept 2-5, 2014, Washington, DC, USA. New Jersey: IEEE Press, pp. 123-128, 2014.

[14] Liang L, Xu W, and Dong X, "Low-complexity hybrid precoding in massive multiuser MIMO systems", *IEEE Wireless Communications Letters*, 3(6): 653-656. 2014.

[15] Fulai Liu1, Zhenxing Sun, Ruiyan Du1,andXiaoyuBai, "AMLSA Algorithm for Hybrid Precoding in Millimeter Wave MIMO Systems" *IOP Conf. Series: Journal of Physics*: Conf. Series -910 , 2017.

[16] Hiroyuki Kasai, "Fast Optimization Algorithm on Complex Oblique Manifold For Hybrid Precoding In MillimeterwaveMimo Systems"*IEEE Global Conference on Signal and Information Processing (GlobalSIP-2018).*

[17] Xianghao Yu, Jun Zhang, and Khaled B. Letaief "Hybrid Precoding in Millimeter Wave Systems: How Many Phase Shifters Are Needed*?" GLOBECOM 2017 - 2017 IEEE Global Communications Conference*, 2017, Singapore.

[18] Xianghao Yu, Jun Zhang, and Khaled B. Letaief "Alternating Minimization Algorithms for Hybrid Precoding in Millimeter Wave MIMO Systems", *IEEE Journal of Selected Topics in Signal Processing*, 2016