Hybrid Precoding/Combining for single-user and Multi-Users in mm-Wave MIMO systems

Nazeerunnisa, Madhavi Tatineni

Abstract—mm-Wave is one of the potential 5G technology predominant at high frequency. The antenna arrays allow parallel transmission to the multiple users. Due to the constraints in hardware in mm-Wave systems, it is difficult to implement conventional multiuser MIMO precoding techniques at mm-Wave. In this paper, initially Hybrid mm-Wave MIMO capacity is compared with conventional MIMO performance. The simulation results demonstrate that the performance loss is due to the assumption of the quantized angle of arrival and departures in dictionary which is very small using OMP algorithms and the capacity approaches the conventional MIMO performance. Then the Hybrid Precoding (HP) at mm-Wave is formulated as a sparse optimization problem in which the hybrid MIMO precoders and combiners are used as the measurement matrices. Here transmit precoding and combining at the receiver is considered with a limited feedback as knowledge of channel may not be practically available. Orthogonal matching Pursuit (OMP) algorithm is used for single-user case and also in multi-user case using simultaneous Orthogonal matching pursuit (SOMP) algorithm. In single user case, numerical results are presented which shows that the proposed algorithm approach is closer to their unconstrained performance even after considering hardware constraints. Multi-user precoding results illustrate that the proposed HP method offers higher Spectral efficiency (SE) compared to analog—only beamforming (AB) and is close to the performance benchmark of optimal digital beamformer.

Keywords—mm-Wave, Hybrid Precoding/combining, multi-user, MIMO, Orthogonal Matching Pursuit

I. INTRODUCTION

Millimeter wave (mm-Wave) technology is emerging as the key holder towards achieving higher data rates [1], [2] in 5G networks, which have the potential to enable the different applications such as wireless HD, V2X (vehicle to everything) and virtual reality communication. However, the practical realization of mm-Wave technology faces several challenges, such as higher path losses [3], increased hardware complexity [1], [4] and severe signal blockage [3]. This has led researchers to explore the practical solutions which address these challenges, without significantly affecting the overall performance of the system. In order to overcome the path-loss in mm-Wave system, highly directional beamforming is required at transmitter (Tx) and receiver (Rx) [5]. Large antennas should be employed at base station (BS) and mobile station (MS) in mm-Wave to achieve high quality communication [6]. The BS need to serve parallelly multiple users with different streams of data, which needs some precoding technique to be applied to generate the signal to be transmitted at the BS. In [7]-[11] proposes analog beamforming for a single user mm-Wave system which controls the angle of the transmitted signal at every antenna through a network of phase shifters implemented in RF domain. It was a part of IEEE 802.11 ad [12], IEEE 802.15, 3c [13] which is a commercial mm-Wave indoor communication standard. A joint design of analog beamforming vectors by the Tx and Rx using adaptive algorithms for beamforming and also code books with multi-resolution were developed [7], [8]. To support multiple streams of data and more efficient beamforming, [6][14][15] proposed HP technique. Thanks to the inherent sparse nature of mm-Wave channels, a low complexity algorithm [6] using the concept of basis pursuit was developed for HP with the assumption of the knowledge of channel. In [14] a hybrid beamforming algorithm with the objective of maximizing the sum-rate or the received signal strength over different subcarriers were proposed for single user MIMO-OFDM system. In [15] HP algorithm that need partial channel knowledge of mm-Wave were developed. The main problem of above mentioned approaches is that it can support only limited number of streams. In multiuser systems, the digital precoding part of the HP gives more freedom in precoder design compared to analog only solutions, which can be exploited to minimize interference between multiple users. Hence designing and developing a low-complexity HP algorithms for multiple user mm-Wave systems is of significant research interest.

In this paper, analysis of HP for single user (SU) and multiple users (MU) based on OMP algorithm is presented and compared with analog only beamforming and with benchmark optimal digital precoding solution.

The paper is structured in the subsequent sections as follows: Section II describes the mm-Wave Hybrid MIMO system Model for MU, Section III describes the Hybrid precoding/combining (HPC) design problem formulation for SU using OMP, Section IV describes the problem formulation in mm-Wave Hybrid MIMO precoding/combining for MU and Section V presents results using MATLAB, which demonstrates the advantage of the proposed hybrid algorithm over AB and HP performance approaching Optimal digital precoder. Last Section VI holds the conclusion with future work.
II. MM-WAVE MULTI-USER HYBRID MIMO SYSTEM MODEL

Consider a MU mm-Wave system model as shown in Fig.1. A BS with \((N_{BS})\) transmitting antennas and RF chains \((N_{RF})\) is assumed to communicate with \(M\) mobile stations (MS) and these MS’s are connected with a limited feedback to BS. Each MS has \((N_{MS})\) antennas as shown in Fig.2. The aim is on representing the mm-Wave MU hybrid MIMO beamforming system model where the BS communicates every MS via only one single stream, hence the total count of streams \(N_c=M\). Also assuming that maximum users that can be served in parallel by the BS is equal to \(N_{RF}\). i.e. \(Mc=N_{RF}\).

In Downlink the BS applies a \(M \times M\) base-band precoder \(F_B\) followed by \(N_{BS} \times M\) RF precoder given by \(F_R = [f_{1}^{R}, f_{2}^{R} ... f_{M}^{R}]\). The signal \(x\) transmitted is represented by (1)

\[
x = F_B F_R x
\]

where \(s = [s_1, s_2, ..., s_M]\) is the \(M\) x 1 transmitted symbols vector, the covariance matrix is \(E[ss^H] = \frac{\rho}{\lambda} I_M\) where \(\rho\) is the average total power transmitted. The total power constraint by normalizing \(F_B\) that is \(\|F_B F_R\|_F^2 = M\).

\(F_R\) RF precoder elements are constrained to be constant magnitude phase factors whose entries are constant modulus satisfying \(\|F_R\|_2^2 = N_{BS}\) and also assuming that the analog RF phase shifter are quantized angles with finite values as \(F_R = \frac{1}{\sqrt{N_{BS}}} e^{i\theta_{u,v}}\), Where \(\theta_{u,v}\) are the quantized angle.

By adopting for simplicity a narrow band block fading channel model given in [6]-[16], the \(m\)th MS observes the signal received before combining as (2)

\[
r_m = H_m \sum_{n=1}^{M} F_B f_n^B s_n + n_m
\]

Where \(H_m\) is the \(N_{MS} \times N_{BS}\) representing the mm-Wave channel matrix between the BS and the \(m\)th MS and \(n_m\) is the Gaussian noise \(n_m \sim N(0,\sigma^2)\).

At the \(m\)th MS, the RF combiner \(w_m\) processes the received signal \(r_m\) as (3)

\[
y_m = w_m^* H_m \sum_{n=1}^{M} F_R f_n^R s_n + w_m^* n_m
\]

Where \(w_m\) has the same constraints as that of RF precoder, i.e. the constant modulus and the quantized angles constraints.

The mm-wave channel have limited scattering so a virtual model is adopted which is a simplified model, thereby considering only azimuth angle \(\theta\) i.e. all the scattering is \(w.r.t\) horizontal beamforming only and neglecting the elevation angle \(\phi\) as (4)

\[
H_m = \sqrt{\frac{N_{BS} N_{MS}}{L_m}} \sum_{l=1}^{L_m} \alpha_{m,l} b_{MS} (\theta_m^{R,l}) b_{RS} (\theta_T^{m,l})
\]

Where \(L_m\) = No. of multipath components \(b_{MS} (\theta_m^{R,l}), b_{RS} (\theta_T^{m,l})\) are the beam steering vectors at the MS and the BS \(\theta\) is the Azimuth angle \(\phi\) is the Elevation angle \(\alpha_{m,l}\) is Complex channel gain \(\epsilon \in [0,2\pi]\) are the \(t\)th path of angles of arrival/ departure (AOAs/AODs) respectively. If uniform linear array is assumed then

\[
b_{BS}(\phi) = \frac{1}{\sqrt{N_{BS}}} [1, e^{j\frac{2\pi}{\lambda} d \sin(\phi)}, ..., e^{j(N_{BS}-1)\frac{2\pi}{\lambda} d \sin(\phi)}]_T
\]

Where \(\lambda\) is the wavelength of signal and \(d\) is the distance between the antenna elements and in similar way the array response at the BS can also be presented.

Fig.1. Downlink system model where BS uses hybrid precoding and a large antenna array to serve multiple users and each MS has a limited feedback to the BS

Fig.2. Block diagram of mm-Wave MIMO system with Hybrid precoding/combining

In section III, channel state information (CSI) \(H\) is assumed to be available at the Rx and is able to obtain \(F_{opt}\) but the knowledge of CSI may not be there in practical systems, so a limited feedback [17]-[19] is proposed to fulfill the requirements of channel information. Assume that Rx acquires H perfect knowledge, calculates \(F_{opt}\) and its hybrid \(F = F_B F_R\) approximation and feedback information about the \(F = F_B F_R\) back to the Tx as shown in Fig.1.

Retrieval Number: B10341292S319/2019©BEIESP
DOI: 10.35940/ijitee.B1034.1292S319
Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication
The mm-Wave HPC problem formulation for a single user is described in section III below.

III. MM-WAVE HYBRID PRECODING/COMBINING (HPC) PROBLEM FORMULATION FOR A SINGLE USER

Consider a mm-Wave system model after precoding and before combining given by (6)
\[ y_{NS} \times 1 = Hx + n = HF_{R}F_{BS} + n = HF_{S} + n \]
After applying RF and BB combiners results in (7)-(8)
\[ \tilde{y} = W_{B}^{H}W_{R}^{H}y = W_{B}^{H}W_{R}^{H}Hx + W_{B}^{H}W_{R}^{H}n \] (7)
\[ \tilde{y} = W_{B}^{H}W_{R}^{H}H \overline{F}_{R}F_{BS} + W_{B}^{H}W_{R}^{H}n = WH_{S} + Wn \] (8)

Where Combiner \( W = W_{R}W_{B} \), \( W_{B}^{H} = N_{R}XN_{RF} \)

Let the noise covariance be \( \sigma_{n}^{2}I \) that is \( E[nn^{H}] = \sigma_{n}^{2}I \) \( (10) \)

Assume ‘s’ comprises of zero-mean Gaussian symbols with covariance given by \( E[ss^{H}] = \frac{\sigma_{n}^{2}}{N_{S}}I \) \( (10) \)

The capacity of the channel is given by (11) using the equation (8)
\[ = \log_{2}[1 + R_{n}^{-1}W_{B}^{H}W_{R}^{H}H \overline{F}_{R}F_{R}F^{H}F^{H}H^{H}W_{B}W_{R}B] \] (11)

Which is complicated and difficult to optimize.

Assume Rx can perform optimal maximum likelihood decoding, the mutual information achieved by Gaussian signaling is given by (12)
\[ I(F_{R}, F_{B}) = \log_{2}[1 + \frac{\sigma_{n}^{2}}{N_{S}}H \overline{F}_{R}F_{R}F^{H}F^{H}H^{H}] \] (12)

The transmit precoding optimization problem can be formulated as (13) as \( F_{B}^{opt} = \arg\max_{F_{B}} I(F_{R}, F_{B}) \) \( (13) \)
\[ s.t \ F_{B} \epsilon \ F_{R} \] set of all \( N_{R}XN_{RF} \) matrices with unit magnitude elements.

Resolving the channel matrix \( H \) as the constituent elements of singular value decomposition (SVD) as given in (14)
\[ H = U_{H}V^{H} \] (14)

Where \( U = N_{R}X \) \( rank(H) \) is receive combiner, values of SVD are in \( \Sigma \) placed in descending order (strongest channel first) following water-filling algorithm and its size is given as
\[ \sum \] \[ = rank(H)X \] \( rank(H) \) is the transmit precoder.

Partition \( V \) and \( \Sigma \) as given in (15)
\[ \Sigma = \begin{bmatrix} \Sigma_{1} & 0 \\ 0 & \Sigma_{2} \end{bmatrix}, \quad V^{H} = \begin{bmatrix} V_{1}^{H} \\ V_{2}^{H} \end{bmatrix}, \quad \Sigma_{1} = N_{S}XN_{T} \] (15)

\( V_{1}^{H} = N_{S}XN_{T} \) recall that the no. of transmitted symbols \( \leq \) \( \text{rank}(H) \).

The mutual information can be approximated as (16)-(17)
\[ I(F_{R}, F_{B}) = \log_{2}[\frac{1}{N_{S}}H \overline{F}_{R}F_{B}F^{H}F^{H}H^{H}I] \] (16)
\[ \approx \log_{2}[\frac{1}{N_{S}}\Sigma_{1}^{2} - (N_{S} - ||V_{1}^{H}F_{R}F_{B}||_{2}^{2})] \] (17)

Actual information loss in mutual information

Where \( F_{R}F_{B} \approx V_{1} \) and the quantity \( ||V_{1}^{H}F_{R}F_{B}||_{2}^{2} \) should be equal to \( N_{S} \) for second part of (17) to be zero.

For a conventional MIMO, the precoding is done at baseband digital precoder \( F_{B} \), therefore the mutual information which is given in (17) can be rewritten as (18)-(19)
\[ = \log_{2}[\frac{1}{N_{S}}\Sigma_{1}^{2} - (N_{S} - ||V_{1}^{H}F_{B}||_{2}^{2})] \] (18)
\[ = \log_{2}[\frac{1}{N_{S}}\Sigma_{1}^{2}] \] when \( F_{B} = V_{1} \) (19)

Thus, reduces to \( F_{B} = V_{1} \), which is the optimal precoder for classical MIMO architecture.

To optimize the mutual information in hybrid precoder \( F_{R}F_{B} \) should be close to \( V_{1} \). Hence the equivalent optimization problem is given by (20)
\[ \arg\min_{F_{R}, F_{B}} ||V_{1} - F_{R}F_{B}||_{2}^{2} \] (20)

Ideally \( V_{1} = F_{R}F_{B} \) is desirable.

The model for channel matrix \( H \) for single-user case is (21)
\[ H_{m} = \sqrt{\frac{N_{BS}N_{MS}}{L}} \sum \alpha_{l}b_{MS}(\theta_{l})b_{BS}(\theta_{l}) \] (21)
\[ = \bar{B}_{MS}(\emptyset)H \bar{B}_{BS}(\emptyset) \] (22)

The transmit array response vectors form basis for row space of \( H \) is \( \bar{B}_{BS}(\theta_{T}) \) and the desired precoder is in (23)
\[ V_{1} = \bar{B}_{BS}(\theta_{T})^{F} \] (23)

Ideally \( \bar{B}_{BS}(\theta_{T})^{F} \) can be made the RF precoder and \( F \) can be made the baseband precoder since the \( \bar{B}_{BS}(\theta_{T}) \) entries are unit magnitude (its entries are not known in general).

However, if \( N_{RF} < L \), then one cannot obtain \( V_{1} \) from \( \bar{B}_{BS}(\theta_{T}) \). Since \( \bar{B}_{BS}(\theta_{T}) \) has \( L \) columns one can linearly combine \( N_{RF} \) columns of \( \bar{B}_{BS}(\theta_{T}) \). \( F_{R} \) can contain only \( N_{RF} \) columns and \( F_{B} \) can contain only \( N_{RF} \) rows. The problem is modified by considering angular grid of size \( G \) with \( G \geq N_{BS}XN_{T} \).

The Dictionary is constructed as \( B_{BS}(\theta_{l}) = [b_{BS}(\theta_{l})] \), \( 1 \leq l \leq G \), and the resulting optimization problem is given (24)
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The angle of arrival at Rx is not known but it will be close to one of the angles of arrivals present in dictionary. If the particular AOA/AOD is not present in the dictionary then it’s to one of the angle of arrivals present in dictionary. If the vectors corresponding to a specific r

Algorithm for mm-Wave Precoder design using SOMP

Input: Opt, Dict, Ryy, numRF
Output: BB, RF (F_R, F_B)

[BB, RF] = SOMP_mmW_precoder (Opt, Dict, Ryy, numRF)

\[ \text{arg } \min \left\| V_1 - B_{BS}(\Theta_B) F_B \right\|_F^2 \]

\[ \text{s.t } \begin{cases} \text{diag} \left( F_B H \right) & = N_{RF}: \text{Enforces sparsity} \\ \left\| B_{BS}(\Theta_B) F_B \right\|_F^2 & = N_s \end{cases} \]

The HP is finally obtained as \( F_B = \frac{\sqrt{f_R} F_B}{\left\| F_B H \right\|_F} \) and the SOMP algorithm returns \( F_R, F_B \) both the precoders. The algorithm doesn’t assume that directional cosine vectors to be known and there will be an approximation error always when \( N_{RF} < L \).

The analog combiner problem occurs in the same manner as analog precoder problem and to achieve the ideal analog combiner by replacing the symbols \( F_B \) and \( H \) by \( W_R \) and \( H_1 \) where \( H_1 = H F_R F_B \), the above algorithm can be applied directly by using minimum mean square error (MMSE) combining.

IV. MM-WAVE HPC PROBLEM FORMULATION FOR MULTI-USERS

To efficiently design the analog RF and digital baseband precoders at the BS and also analog combiners at the MS’s, the sum-rate of the system is maximized. The signal received at the \( m^{th} \) MS in equation (2) is further processed by the RF combiner \( w_m \) and the rate achieved by the user \( m \) is given

\[ R_m = \log_2 \left( 1 + \frac{\left| \sum_{w_m} \left| w_m h_m f_{mR} f_{mB} \right| \right|^2}{\sum_{w_m} \left| w_m h_m f_{mR} f_{mB} \right|^2 + \sigma^2} \right) \]

The system sum rate is given by (26)-(27)

If the performance metric is the sumrate then the precoding problem is to find \( F_B, \{ f_{mB} \} \) \( m = 1, \ldots, M \), \( w_m \) \( m = 1 \), that simplifies to

\[ = \arg \max_{w_m} \sum_{m=1}^{M} \log_2 \left( 1 + \frac{\left| \sum_{w_m} \left| w_m h_m f_{mR} f_{mB} \right| \right|^2}{\sum_{w_m} \left| w_m h_m f_{mR} f_{mB} \right|^2 + \sigma^2} \right) \]

V. SIMULATION RESULTS

To simulate results, MATLAB R2019a simulator is used. Consider the Tx and Rx consisting of a uniform linear array with \( N_T = N_{RF} = 32 \), \( N_T = 6 \) which is set equal to \( N_M \) and \( L \) is the sparsity level which is set to 8. The AOA/AOD space is divided into \( G = 64 \) grids and a dictionary is created mapping to array response vectors of all the possible angles of arrivals/ departures.

The results shows that the capacity of OMP based hybrid precoder approximating Conventional MIMO whose results are illustrated in figure 3.

The procedure for Hybrid Precoder design in mm-Wave MIMO system using SOMP is presented below:-

Step 1:
Set up the required parameters for mm-Wave hybrid precoder design as shown in Table-1 below:

Step 2:
Initialize the Grid quantized transmit/receive array beam response vectors and generate their dictionary matrix. Here the \( \cos \theta \) values are directly generated not the angles which is given by \( \text{dirCos}=2G^* (1-1) -1, \text{for } I=1:G, \text{for } K=1:Nt \)

\[ B_T(K,I)=1/\sqrt{t} \times \exp(j \pi^* (K-1)^* \text{dirCos}) \]

\[ B_R=B_T; \text{for simplicity} \]
Step 3:
Generate Channel gain and Channel matrix and compute singular value decomposition (SVD) of H
\[
\text{chGain} = \frac{1}{\sqrt{N_T \times N_R}} [(\text{randn}(L,1)+j \times \text{randn}(L,1));
\]
\[
\text{H} = N_T \times N_R \times \text{B_R_genie} \times \text{diag(chGain)} \times \text{B_T_genie}';
\]
\[
[U,S,V] = \text{svd(H)};
\]

Table I: Set up Simulation parameters

<table>
<thead>
<tr>
<th>Simulation Parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(N_T)</td>
<td>32</td>
</tr>
<tr>
<td>(N_R)</td>
<td>32</td>
</tr>
<tr>
<td>RF chains</td>
<td>6</td>
</tr>
<tr>
<td>(N_{\text{Beam}})</td>
<td>24</td>
</tr>
<tr>
<td>Grid (G)</td>
<td>64</td>
</tr>
<tr>
<td>ITER</td>
<td>100</td>
</tr>
<tr>
<td>L sparsity</td>
<td>8</td>
</tr>
<tr>
<td>(\text{dirCos})</td>
<td>(-1,1)</td>
</tr>
<tr>
<td>SNRdB</td>
<td>-5:5:10</td>
</tr>
</tbody>
</table>

Step 4:
Obtain optimal unconstraint precoder \(F_{\text{opt}} = V(:,1:Ns)\)

Step 5:
OMP based Hybrid precoder design is implemented
\[
[F_{\text{BB}},F_{\text{RF}}] = \text{SOMP}_\text{mmW_precoder}(F_{\text{opt}},B_T,\text{eye}(t),\text{numRF})
\]
\[
F_{\text{BB}}\_\text{NORM} = \text{sqrt}(Ns)/(\text{norm}(F_{\text{RF}}*F_{\text{BB}},'fro'))*F_{\text{BB}}
\]

Step 6:
Determine the Capacity of optimal unconstraint MIMO precoder/combiner.
\[
\text{C}_\text{MIMO}(i_{\text{snr}}) = \text{C}_\text{MIMO(i}_{\text{snr}})+\text{mimo_capacity}(\text{Wmse}_{\text{opt}}*H_{\text{Fopt}},1/\text{Ns}*\text{eye}(\text{Ns}),\text{np}*\text{Wmse}_{\text{opt}}*\text{Wmmse}_{\text{opt}});
\]

Step 7:
OMP based receive hybrid combiner design and the capacity of OMP-based precoder/combiner.
\[
[W_{\text{BB}},W_{\text{RF}}] = \text{SOMP}_\text{mmW_precoder}(\text{Wmmse}_{\text{Hyb}},B_R,\text{numRF});
\]
\[
\text{C}_\text{HYB}(i_{\text{snr}}) = \text{C}_\text{HYB(i}_{\text{snr}})+\text{mimo_capacity}(\text{WBB}**\text{WRF}*H*\text{FRF}*F_{\text{BB}}\_\text{NORM},1/\text{Ns}*\text{eye}(\text{Ns}),\text{np}*\text{WBB}**\text{WRF}*\text{WRF}*W_{\text{BB}});
\]
\[
\text{C}_\text{MIMO} = \text{C}_\text{MIMO}/\text{ITER};\text{C}_\text{HYB} = \text{C}_\text{HYB}/\text{ITER};
\]

with Hybrid MIMO using OMP estimator for \(N_{\text{RF}}=\text{Ns}=6\)

In Fig.3, the parameters are set up as mentioned in the Table 1, the performance analysis of conventional MIMO is compared with the Hybrid MIMO using OMP algorithm. It portray’s that the performance loss is due to assumption of the quantized angle of arrival and departures in dictionary which is very small in OMP algorithm and the capacity approaches the conventional performance. OMP algorithm performs the computation with very few number of samples efficiently, shows an advantage over conventional MIMO estimators.

In Fig.4 spectral efficiency (SE) obtained in a 64 X 16 with a planar array at both Tx and Rx. \(N_{\text{RF}} = 4, N_s = 1 \text{ or } 2\) streams and over 500 channel realization. The demonstrated results portrays that the proposed OMP based sparse precoding and combining is accurately approximating the optimal unconstraint solution in comparison to conventional analog beamsteering. It is observed that SE is lower by 7b/s/Hz in analog beamsteering when compared to optimal and sparse precoding/combing which is close to 15 b/s/Hz and the performance gap is increasing as SNR varies from -20 dB to 20 dB as observed in Fig.4.

Fig.4. SE vs SNR for 64 X16 mm-Wave system \(N_{RF} = 4, N_s = 1 \text{ or } 2\) streams (single user)

In Fig. 5, Consider the system model in section II where a BS employs 8 x 8 UPA with four MS’s, the AOA/AOD are distributed uniformly in \([-\pi/2, \pi/2]\) is assumed. The performance achieved by HP is compared with SU rate and with beamsteering. The results illustrates that the performance of HP is close to SU (without interference) performance, which is due to the cancellation of residual (MUI) multi-user interference.

Fig.5. SE vs SNR(db) using HP and beamsteering algorithm with channel knowledge (Multi-users=4)
VI. CONCLUSION

A Comparative analysis for HPC for mm-Wave MIMO system with analog beamsteering and optimal digital precoding for single user and multi-user have been presented using OMP algorithm. The MATLAB simulations illustrates the outperformance of OMP algorithm which gives high capacity compared to ABand approaches the optimal digital precoding. The objective of this paper was to analyse and improve hybrid precoding/combining so that it can be incorporated to improve spectral efficiency and capacity in mm-Wave MIMO system for sparse channel estimation. Future extension will be to use the Artificial Intelligence(AI) based learning algorithms to enhance hybrid precoding/combining performance further to efficiently estimate sparse channels in mm-Wave MIMO systems.

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