

Hybrid Precoding Design Using MMSE Baseband Precoder for mm-Wave Multi-User MIMO Systems

Farah Raisa, Md. Rafiqul Islam, Khaizuran Abdullah, Asif Reza

Abstract— For future 5G wireless communication networks, millimeter-wave (mmWave) cellular systems is considered to be the key enabling technology because of its high data rates, low latency, high system capacity, and huge available bandwidths. However, multiuser networks in mmWave frequency bands encounter high path loss and interference, thus degrading the performance. Applying large antenna arrays at the base stations (BS) in order to achieve high beamforming gains with the help of precoding techniques is an efficient way of improving the performance of the system. Although multi-user beamforming can improve spectral efficiencies, full digital beamforming strategies used in the conventional microwave systems increase the hardware cost and consumes high power for large number of antennas in mmW systems. In this paper, a low-complexity multi-user hybrid precoding structure is proposed for mmWave multiple input multiple output (MIMO) channels utilizing Minimum Mean Square Error (MMSE) precoders at the BS with perfect channel knowledge. Simulations show that the achievable rate obtained by the proposed hybrid precoding scheme is very close to the single-user rate and also performs better compared to other hybrid precoding approaches.

Keywords: MIMO, Millimeter-wave, mmWave, Hybrid Precoding, MMSE

I. INTRODUCTION

To obtain high performance and throughput, millimeter wave networks are one of the efficient technologies which can be utilized to apply in future 5G wireless systems. The spectrum band that ranges from 30 GHz to 300 GHz is generally known as the mm-waves frequencies [1]. As millimeter-Wave (mmW) spectrum has very small wavelength, so the available bandwidths are larger than the bandwidth those are used today. As a result, there is more available spectrum and a large number of small antennas can be used in this frequency band which will lead to greater system capacity. So, it is expected to play an important role for the future 5G wireless networks [2]. However, there are a number of challenges that mmWave is going to face and before making it widely used, it must be managed and solved in order to ensure maximum efficiency. Millimeter-Wave is

subjected to severe attenuation and path loss due to noise and interference. So, these problems can be solved by antenna Beamforming and multi user MIMO.

Implementation of analog beamforming for mmWave systems using phase-shifters is popular due to low cost and simplicity of the structure [3-6]. The transceivers operating at high frequencies as in the case of millimeter wavebands support analog beamforming since the digital beamforming makes the system more complex with a large number of antennas. Analog beamforming has been the major support particularly for the indoor mm-wave systems adopting different beamforming training protocols [3-4]. To overcome the high path loss issue of the mm-wave frequencies, a large number of antennas are aligned and the RF chains are kept as minimum as possible to maintain simple circuit and low power consumption. The beam pointing angles are needed to be aligned to face each other to form beam angle pair. However, these proposed methods were only applicable for single-stream transmission and also has large training overhead for large number of users. The performance of these low-power analog beamforming approaches, is very poor and not completely suitable for mm-wave channels. Fully digital beamforming architectures used in broadband microwave [7] is impractical for millimeter-wave systems due to high hardware complexity and power consumption.

The efficient beamforming architecture for mm-wave systems needs to be designed with both analog and digital processing [8-17]. Hybrid analog-digital beamforming involves dividing the MIMO processing into both analog and digital domain for multi-user data transmission with minimum interference. Limited number of radio frequency (RF) chains are utilized that forwards the processing of the digital baseband superseded by the analog beamforming. In order to maximize the average received SNR and thus the link budget, joint analog-digital beamforming algorithm was developed [9] with perfect Channel State Information (CSI) where the number of radio frequency chains were reduced with negligible performance loss to minimize the cost. Zero forcing (ZF) and phased zero-forcing (PZF) hybrid precoding scheme is proposed in several literatures [14] [15] performing low-dimensional zero forcing precoding at the baseband. The analog RF precoder is designed to obtain the large array gain and after that ZF precoding is carried out depending on the channel.

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The hybrid BF algorithm for single-user mm-wave systems which assumes only limited knowledge of the channel [14] considers both the reciprocal and sparse environment. However, these proposed hybrid precoding algorithms do not utilize the characteristics of the mm-wave channel properly. As a result, when applied to mmW systems, these approaches will consume high power due to the use of high resolution ADC at the receiver. Efficient beam-forming design for millimeter-wave channels considering the special characteristics of the channel is needed that can bring benefit in practical application for the massive number of antennas and which is compatible for millimetre-wave frequency bands.

In this paper, an efficient hybrid precoding design for mmWave channel with comparatively low-complexity is proposed where precoding is done in both analog and digital domains for multi-user scenario. In this design, RF precoding is done to increase the transmit power and after that MMSE baseband precoding is adapted for multi-user system to mitigate the inter-user interference. Rest of the paper is organized as follows: The system model for the mmWave hybrid beamforming structure is discussed in section 2. In section 3, the proposed hybrid MMSE precoding design is presented and analysed under perfect CSI in section 4. Simulation results are illustrated in section 5 and finally the paper is concluded in section 6.

II. SYSTEM MODEL

In the system model for mmWave propagation, it is considered that N_t number of transmit antennas and N_{RF} number of chains are connected at the BS. The base station communicates with the mobile stations of K users, each of them equipped with N_r number of receive antennas. In multi-user beamforming system, each of the users supports single-stream transmission between the BS and the MS. So, the number of data streams is equal to the number of total user K . It is also considered that the number of RF chains at the BS is same as the highest number of users being served at the same time i.e., the number of users are less than the number of RF chains. Moreover, it is assumed that K number of N_{RF} will be used by the base station in order to serve the users. The transmitter at the BS executes $K \times K$ baseband precoder, F_B , and $N_t \times K$ RF precoder, F_R . The transmitted signal is then given by,

$$x = F_R F_B s \tag{1}$$

In this equation, s is the $K \times 1$ transmitted symbol vector such that, $E[ss^*] = \frac{P}{K} I_K$, where, P is the average transmit power. Analog phase shifters are being used to execute F_R , so its entries are normalized in order to satisfy $|[F_R]_{m,n}|^2 = N_t^{-1}$. Moreover, each entry of F_R varies in phase-only and we normalize the magnitude so that it satisfies $[F_R]_{m,n} = \frac{1}{\sqrt{N_t}} e^{j\phi_{m,n}}$, where $\phi_{m,n}$ is the quantized angle. The total power constraints at the BS is accomplished by normalizing F_B such that $\|F_R F_B\|_F^2 = K$. A narrowband

channel model is adopted [14] [17] where received signal observed by the k^{th} user,

$$r_k = H_k \sum_{n=1}^K F_R f_n^B s_n + n_k \tag{2}$$

Where, H_k is the mm-wave channel matrix between BS and MS with dimension $N_r \times N_t$, n_k is the additive Gaussian noise and $n_k \sim \mathcal{N}(0, \sigma^2 I)$.

A. Channel Model

The hybrid precoders (F_R, F_B) and the hybrid combiners (W_R) are investigated depending on the channel matrix H . In order to analysis the performance of the proposed hybrid precoding, a geometric mm-wave channel model is adopted with limited scattering characteristics for the channel, with each scatterer having a single propagation path. It is assumed that the channel is the sum of propagation paths, each having a scatterer and having L_k number of scattering clusters for the channel k . Channel H_k from [14] can be expressed as

$$H_k = \sqrt{\frac{N_t N_r}{L_k}} \sum_{l=1}^{L_k} \alpha_{k,l} a_r(\theta_{k,l}) a_t^*(\phi_{k,l}) \tag{3}$$

Where, $\theta_{k,l}$ is the angle of arrival (AoA) and $\phi_{k,l}$ is the angle of departure (AoD) of the l^{th} path. $\alpha_{k,l}$ is the l^{th} path's complex gain adding the path loss, and $a_r(\theta_{k,l})$ and $a_t(\phi_{k,l})$ are the array response vector of the antennas of the MS and BS respectively.

The simulation of the proposed design is based on two types of antenna arrays, i.e., uniform planar arrays (UPA) and uniform linear arrays (ULA). The array response vector for ULA antennas at the BS can be defined as

$$a_t(\phi_{k,l}) = \frac{1}{\sqrt{N_t}} [1, \exp(j \frac{2\pi}{\lambda} d \sin(\phi_{k,l})), \dots, \exp(j(N_t - 1) \frac{2\pi}{\lambda} d \sin(\phi_{k,l}))]^T \tag{4}$$

Where, λ is the carrier wavelength, d is the distance between two antenna elements.

3. HYBRID MMSE PRECODING FOR MULTI-USER MIMO

Designing hybrid precoders at the BS and combiners at the MSs efficiently to maximize the total sum rate of the system is the main objective of this thesis. The achievable rate for the user k at the MS can be written as in [14], after processing the received signal utilizing the combining vector,

$$R_k = \log_2 \left[1 + \frac{\frac{P}{K} |w_k^* H_k f_k^B|^2}{\sum_{n \neq k} \frac{P}{K} |w_k^* H_n f_n^B|^2 + \sigma^2} \right] \tag{5}$$

Total sum-rate of the system is given by, $R = \sum_{k=1}^K R_k$ (6)

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chosen from different beamforming codebooks. As the analog beamsteering codebooks are previously used and shown to have better performance for single-user precoding schemes, in this paper this beamsteering codebooks are adopted for selecting the RF beamforming vectors. Here, for channels with single path, the beamforming vectors have similar type of array response vector which can be represented by a simple angle. Let \mathcal{F} and \mathcal{W} be the RF precoding vector codebook and RF combining codebook respectively.

Considering the sum-rate as the performance metric, \mathbf{F}_R^* , $\{f_k^B\}_{k=1}^K$ and $\{w_k^*\}_{k=1}^K$ are needed to be obtained from the equation (4) to solve

$$\begin{aligned} & \{\mathbf{F}_R^*, \{f_k^B\}_{k=1}^K, \{w_k^*\}_{k=1}^K\} = \arg \max (R_s) \\ & = \arg \max \sum_{k=1}^K \log_2 \left(1 + \frac{\frac{P}{K} |w_k^* \mathbf{H}_k \mathbf{F}_R f_k^B|^2}{\frac{P}{K} \sum_{n \neq k} |w_n^* \mathbf{H}_n \mathbf{F}_R f_n^B|^2 + \sigma^2} \right) \\ & \text{subject to, } \mathbf{F}_R]_{:,k} \in \mathcal{F}, k = 1, 2, \dots, K, \\ & w_k \in \mathcal{W}, k = 1, 2, \dots, K, \\ & \|\mathbf{F}_R [f_1^B, f_2^B, \dots, f_K^B]\|_F^2 = K. \end{aligned} \quad (7)$$

However, it is infeasible and unmanageable to obtain explicit solution of this maximization of the total sum-rate due to certain factors. The solution for the above equation needs to search for possible \mathbf{F}_R and $\{w_k^*\}_{k=1}^K$ combinations over the $\mathcal{F}^K \times \mathcal{W}^K$. Moreover, the baseband precoder \mathbf{F}_B is needed to incorporate with the RF beamforming vectors which needs the channel or effective channel feedback, resulting in large feedback and training overhead for this solution. A modified algorithm is proposed for mm-wave multi-user MIMO for a large number of antenna that can have better performance than the previous one with a very small training and feedback overhead.

The analog RF precoders and RF combiners are designed at the BS and MS respectively for single-user scenario avoiding the inter-user interference and the power of the signal per user is maximized without estimating the channel. The BF vectors for the k th user are designed in such a manner so that at the signal power is highest at the k th MS. The RF precoding scheme here is the typical analog precoding for single-user system that is used in other literatures [10] [12]. Efficient beam alignment algorithm is used which exploits the BF codebook to maximize the SNR. The hierarchical codebook utilizes a distance metric which can be optimized by using proper subarray methods.

After this stage, the digital baseband precoder is constructed for multi-user MIMO and inter-user interference in handled. Effective

channels, $\bar{h}_k = w_k^* \mathbf{H}_k \mathbf{F}_R$, $k = 1, 2, \dots, K$, are trained by the base station with the mobile stations. A random vector quantization (RVQ) codebook (\mathcal{F}) is used to quantize these effective channels by their corresponding MS (k), and then the index of the channel vector is fed to the base station with B_b bits. The MMSE (Minimum Mean Squared Error) precoding is then constructed in the BS depending on quantized channels.

IV. PERFORMANCE ANALYSIS WITH PERFECT CSI

In this section, the spectral efficiency is analysed which is achieved by the RF and baseband hybrid precoders. The performance is analysed for massive MIMO with a large number of transmit and receive antennas and with single-path channels. Assuming that the effective channel knowledge is perfect and the values of RF beamsteering angles are continuous. It is also assumed that all the codebooks including the RF codebooks for the BS and MS and the RVQ codebook has the size of infinity. It is considered that the channel is single-path so the scattering path $L_k = 1$ for $k = 1, 2, 3 \dots K$. The effective channel can be written for k user after constructing the analog precoders, $\bar{h}_k = w_k \mathbf{H}_k \mathbf{F}_R = \sqrt{N_t N_r} \alpha_k a_t^*(\phi_k) \mathbf{F}_R$

The effective channel matrix $\bar{\mathbf{H}}$ is given by, $\bar{\mathbf{H}} = \mathbf{C} \mathbf{A}_t^* \mathbf{A}_r$, where \mathbf{C} is the diagonal matrix with dimension $K \times K$ and $[\mathbf{C}]_{k,k} = \sqrt{N_t N_r} \alpha_k$. The MMSE precoder of digital baseband depending on the effective channels can be expressed as, $\mathbf{F}_B = \bar{\mathbf{H}}^H (\bar{\mathbf{H}}^H \bar{\mathbf{H}} + \alpha \mathbf{I})^{-1}$, where α is the normalization factor and it is normalized to adjust elements according to the power constraints $\|\mathbf{F}_R f_k^B\|^2 = 1$. The elements of the diagonal matrix are $\sqrt{\frac{N_t N_r}{(\mathbf{A}_t^* \mathbf{A}_t)_{k,k}^{-1}} |\alpha_k|}$. Then the achieved rate can be written as

$$R_k = \log_2 \left[1 + \frac{SNR}{K} |\bar{h}_k^* f_k^B|^2 \right] = \log_2 \left[1 + \frac{SNR}{K} \sqrt{\frac{N_t N_r}{(\mathbf{A}_t^* \mathbf{A}_t)_{k,k}^{-1}} |\alpha_k|^2} \right] \quad (8)$$

For single-user, the achievable rate is given by

$$R_{single} = \log_2 \left[1 + \frac{SNR}{K} N_t N_r |\alpha_k|^2 \right] \quad (9)$$

As the precoders and combiners are designed according to the algorithm considering the assumptions stated before, the achievable rate of user k and the single user achievable rate increases with the similar slope when SNR is high. The difference between these two types of achievable rates is always constant as it only depends on the number of users and the number of transmitters.

The effective channel $\bar{\mathbf{H}}_v$,

$$\bar{\mathbf{H}}_v = \mathbf{D}_v \mathbf{P}_v \quad (10)$$

\mathbf{D}_v represents the diagonal matrix and \mathbf{P}_v is the $K \times K$ matrix

Digital MMSE precoder,

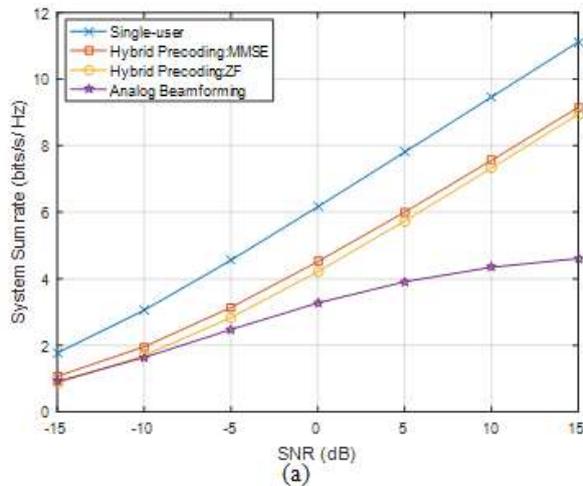
$$\mathbf{F}_B = \bar{\mathbf{H}}^H (\bar{\mathbf{H}}^H \bar{\mathbf{H}} + \alpha \mathbf{I})^{-1} \mathbf{A} \quad (11)$$

Where, α is the regularization factor and $\alpha = \frac{N_r \sigma_n^2}{\sigma_s^2}$, where σ_n^2 and σ_s^2 are noise variance and average transmit power respectively. So, the sum rate of user K is given by



$$R_K = \log_2 \left(1 + \frac{SNR}{K} |\bar{h}_k^* f_k^B|^2 \right) \quad (12)$$

This equation represents the achievable rate for user k obtained by the proposed hybrid precoding structure. In the next section, the results of the simulation comparing the



spectral efficiencies of the proposed design and other different beamforming approaches are presented.

V.SIMULATION RESULTS

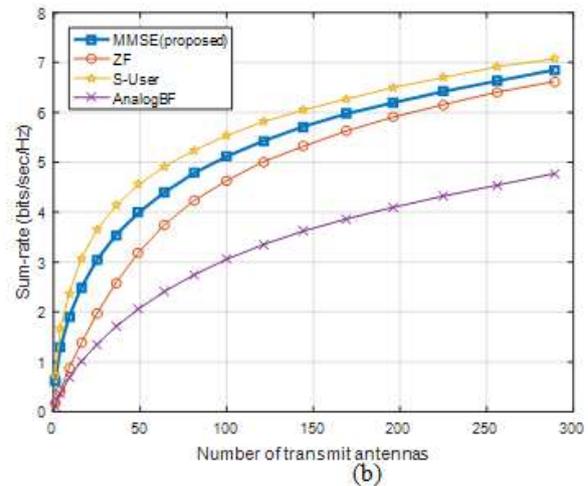


Fig. 1. Results of Sum-rate Vs SNR curve for hybrid Precoding mmW systems (a) comparison of different schemes, (b) varying the number of transmit antennas.

In this section the performance of the proposed hybrid pre-coding design is studied using numerical simulation and compared with other hybrid precoding designs of the literature discussed in the previous sections. The simulation is carried out in MATLAB simulator and in three different systems. MU-MIMO is considered in this analysis with BS antennas and MS antennas. Four mobile stations are considered and each having single-path transmission. The effective channel is assumed to be perfect with AoDs and AoAs to be uniformly distributed. The azimuths and elevations are uniformly distributed in and respectively. Noise variance is assumed to be 1 and the SNR is . The achievable rates of the proposed hybrid MMSE analog/digital precoding technique is analyzed and compared with the single-user rate, analog beamforming and hybrid ZF precoding systems and results show that the proposed hybrid precoding scheme performs very close to single-user rate and ZF hybrid precoding and also achieves better gain over the analog beamforming approach. Fig. 1(a) demonstrates the achievable sum-rate of different precoding approaches. For massive MIMO mmWave systems, with a large number of antennas, the performance of the proposed scheme increases significantly. The simulation of the sum rate of the proposed hybrid precoding varying the BS antennas with fixed is shown in fig. 1(b).

VI. CONCLUSION

In this paper, low-complexity hybrid precoding design is presented for mmWave multi-user communication with MMSE baseband precoding. For mmWave networks with perfect channel conditions, analog beamforming is not feasible due to low sum rate. Digital precoding system increase the performance but at the cost of high complexity. So, integrating both analog and digital processing in the BS

can give better throughput. Analyzing the proposed design under perfect channel, this approach has shown better performance compared to other hybrid precoding approaches.

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