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Error Performance Analysis of Millimeter Wave Massive MIMO System with Hybrid Precoding

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Abstract

The application of millimeter wave (mmWave) communication to massive multiple-input-multiple-output (MIMO) systems has been recognised as one of the enabling technologies to meet the performance goals of the fifth-generation (5G) and beyond wireless networks. Digital precoding techniques are impractical in such systems as they require a dedicated RF chain for each antenna element and hence incur very high cost, power consumption, and space constraints. Hybrid precoding has been recognised as more sui in such systems as it can make an optimum trade-off between system performance and hardware complexity. In this paper, we evaluate downlink bit error rate (BER) performance of single-user (SU) mmWave massive MIMO system equipped with hybrid precoding. We derive an approximate analytic expression of BER for such systems, which can be applied to any hybrid precoding, combining and modulation technique. We also present a low-complexity hybrid precoding (LC-HP) technique suitable for mmWave systems and evaluate its error performance with the help of derived BER expression. The simulation results validate the correctness of the derived analytic expression.

Keywords: Millimeter wave, massive MIMO, hybrid precoding, bit error rate, computational complexity

1. Introduction

The amalgamation of massive MIMO and millimeter wave (mmWave) communication in the largely untouched 30–300 GHz frequency band has been a driving force to fuel the growth of 5G and beyond wireless networks. Massive MIMO enables aggressive spatial multiplexing and creates highly directional beams to overcome pathloss caused by mmWave frequencies. Small wavelength of mmWave frequency facilitates the implementation of large number of antennas at either side of the radio link. This is particularly attractive in mobile devices such as cell phones, as it enables embedding large antenna arrays in small space. As the number of antennas in a MIMO system increase, it becomes impractical to deploy digital precoding techniques due to high cost, power consumption and space constraints caused by excessive number of RF chains [1]. The situation is even more challenging in mmWave systems due to large number of antennas at both ends of the radio network [2]. Hybrid precoding is the best solution in such scenarios as it offers optimum balance between high-performance digital precoding and low-cost analog beamforming [1], [3], [4]. It can exploit the limited scattering nature of mmWave channels to reduce the number of RF chains to as low as the number of propagation paths. The basic idea is to divide the signal processing task into digital and analog domains. The digital processor requires small number of RF chains. It is followed by low-cost analog processor consisting of a network of large number phase shifter elements. Similar hybrid structure is implemented for combiners at the receiver for signal processing. However, the constant magnitude limitation of phase shifters and the coupling between hybrid precoders/combiners at the transmitter/receiver make the design of hybrid precoders/combiners a non-convex optimisation problem [5], [6].

Bit error rate (BER) is considered to be one of the most important parameters for assessing end-to-end performance of any wireless communication system. It measures system reliability and indicates how effectively detection process takes place at the receiver. For sub-6 GHz (microwave) frequency, the propagation channel in conventional MIMO and massive MIMO, is assumed to have rich scattering conditions. Authors in [7] derived analytic expression of bit error probability for conventional MIMO assuming Rayleigh fading channel and zero-forcing (ZF) precoding with full channel state information (CSI) at the transmitter. For the same channel conditions, the authors of [8] and [9] analysed the error performance of ZF receiver and minimum mean-squared error (MMSE) receiver respectively in the presence of channel estimation errors and validated their analytic results through simulations. Authors of [10] investigated the error performance of MIMO receiver in Rician fading channel. For the massive MIMO system, authors of [11] investigated error performance for the multi-user (MU) case with maximum ratio combining (MRC) receiver. The analysis was done assuming Rayleigh fading and availability of CSI to the receiver. Authors of [12] derived pairwise error probability for ZF and MMSE receivers in a multi-cell scenario where the base station (BS) possess CSI of its users only. In order to reduce power consumption in massive MIMO, application of low-resolution analog-to-digital converters (ADCs) have been widely considered [13]. Error performance of massive MIMO with low-resolution ADC has been investigated for downlink in [14] and uplink in [15] with simulation studies.

The channel models adopted for conventional MIMO and massive MIMO at microwave frequency cannot be extended to mmWave channels due to their sparse scattering nature. In

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[16], authors developed a mathematical framework to derive upper bound for BER of single-user (SU) mmWave MIMO link in the uplink direction considering pathloss, directional antennas and line-of-sight (LoS) scenario. For the MU-MIMO link with mmWave communication, authors of [17] designed hybrid precoders based on constrained MMSE (CMMSE) criterion for minimising average BER and established that the proposed method is superior to conventional MMSE based methods [18].

Contributions

- Different from the previous works in literature, in this paper, we derive an approximate analytic expression of BER for evaluating downlink error performance of SU mmWave massive MIMO system adopting hybrid precoding transceiver architecture and minimum distance detection (MDD) approach. The BER expression can be applied to any arbitrary hybrid precoding, combining and modulation technique.
- We present the low complexity hybrid precoding (LC-HP) technique to efficiently design hybrid precoders/combiners at the transmitter/receiver for the SU mmWave system. The BER of the designed system is investigated by conducting simulation studies and comparing with analytic results.
- We also compare the BER performance of the designed system with OMP-based hybrid precoding [19] and digital precoding.

In this paper, conjugate transpose, transpose, pseudo inverse and expectation operators are denoted by $(\bullet)^H$, $(\bullet)^T$, $(\bullet)^\dagger$ and $\mathbb{E}\{\bullet\}$ respectively. Bold uppercase, bold lowercase and normal face letters stand for matrices, vectors and scalars respectively. $||\mathbf{N}||_F$ represents Frobenius norm, and $|\mathbf{N}|$ represents determinant of matrix $\mathbf{N}$, $||\mathbf{n}||$ denotes Euclidean norm of vector $\mathbf{n}$. The notations $\mathbf{N}(:,b)$ and $\mathbf{N}(a,b)$ stand for the b-th column and (a, b)-th element of $\mathbf{N}$ respectively. $Re\{\bullet\}$ denotes the real part of a complex variable. $\mathbf{I}_y$ symbolises an $y \times y$ identity matrix. Symbol $\mathbb{C}^{x\times y}$ represents the set of complex matrices of dimension $x \times y$. Gaussian Q-function is represented by $Q(\bullet)$.

System Model

Consider Fig. 1 which shows the downlink scenario of a wireless communication system in which a BS is equipped with N_T antennas and is sending N_S data streams to a mobile station (MS) equipped with N_R antennas. Both ends of the radio link adopt hybrid signal processing architecture. The number of RF chains at the BS and MS are L_T and L_R respectively such that $N_S \le L_T \le N_T$ and $N_S \le L_R \le N_R$. Signal vector $\mathbf{s} \in \mathbb{C}^{N_S\times 1}$ is first processed by the digital precoder $\mathbf{F}_{BB} \in \mathbb{C}^{L_T\times N_S}$ followed by the analog precoder $\mathbf{F}_{RF} \in \mathbb{C}^{N_T\times L_T}$ before being fed to the transmitter antennas. Total transmit power is normalized as $\mathbb{E}\{\mathbf{s}\mathbf{s}^H\} = \left(\frac{1}{N_S}\right)\mathbf{I}_{N_S}$. Considering frequency flat fading channel, the signal vector $\mathbf{y} \in \mathbb{C}^{N_R\times 1}$ received at the MS antennas is

$$\mathbf{y} = \sqrt{\rho}\mathbf{H}\mathbf{F}_{RF}\mathbf{F}_{BB}\mathbf{s} + \mathbf{n} \quad (1)$$

where $\mathbf{H} \in \mathbb{C}^{N_R\times N_T}$ is the channel matrix with $\mathbb{E}\{||\mathbf{H}||^2{}_F\} = N_T N_R$ and ρ is the average power of the received signal. Symbol $\mathbf{n}$ denotes additive complex Gaussian noise vector consisting of independent and identically distributed random variables with zero mean and variance σ_n^2. Digital precoder is normalized as $||\mathbf{F}_{RF}\mathbf{F}_{BB}||^2{}_F = N_S$ to satisfy the total transmit power constraint. The signal after receiver combining is

$$\tilde{\mathbf{y}} = \mathbf{W}_{BB}^H\mathbf{W}_{RF}^H\mathbf{y} = \sqrt{\rho}\mathbf{W}_{BB}^H\mathbf{W}_{RF}^H\mathbf{H}\mathbf{F}_{RF}\mathbf{F}_{BB}\mathbf{s} + \mathbf{W}_{BB}^H\mathbf{W}_{RF}^H\mathbf{n} \quad (2)$$

where $\mathbf{W}_{RF} \in \mathbb{C}^{N_R\times L_R}$ and $\mathbf{W}_{BB} \in \mathbb{C}^{L_R\times N_S}$ are analog and digital combiners at the receiver respectively. Analog precoder and combiner are implemented using low-cost phase shifter elements of constant magnitudes. Hence, they can alter only the phase of the signal and their elements are restricted to be of constant magnitudes as $|\mathbf{F}_{RF}(a,b)| = \frac{1}{\sqrt{N_T}}$ and $|\mathbf{W}_{RF}(a,b)| = \frac{1}{\sqrt{N_R}}$. On the other hand, digital precoder and combiner have no such hardware restriction. Both BS and MS are assumed to have prior knowledge of channel.

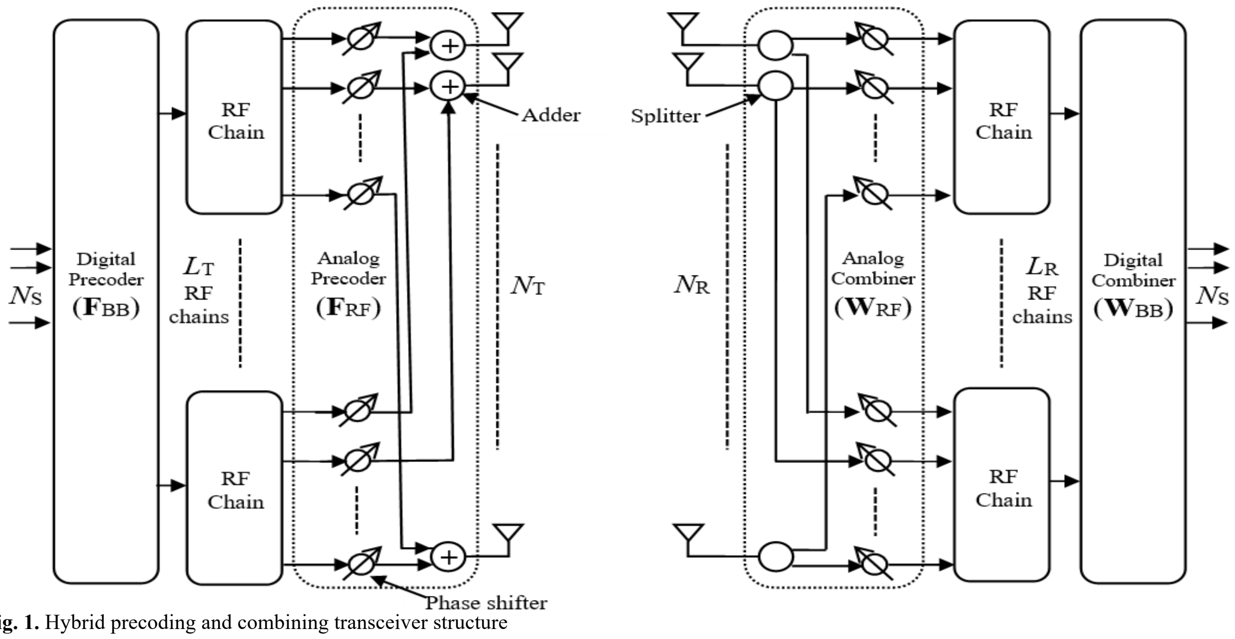

Fig. 1. Hybrid precoding and combining transceiver structure

Channel Model
Since mmWave communication suffers from high path loss and poor scattering, the commonly used Rayleigh fading channel model, which assumes rich scattering, cannot be adopted for mmWave channels. Hence mmWave channel is modelled as consisting of N_{P} propagation paths between BS and MS based on the extended Saleh-Valenzuela model as follows [20]

$$\mathbf{H} = \sqrt{\frac{N_{\mathrm{T}}N_{\mathrm{R}}}{N_{\mathrm{P}}}} \sum_{p=1}^{N_{\mathrm{P}}} \alpha_p \mathbf{a}_{\mathrm{R}}(\phi_p^R, \theta_p^R)\mathbf{a}_{\mathrm{T}}^H(\phi_p^T, \theta_p^T) \quad (3)$$

where α_p denotes complex channel gain of p-th propagation path. For the p-th path, $\phi_p^R(\theta_p^R)$ and $\phi_p^T(\theta_p^T)$ denote azimuth (elevation) angles of arrival (AoAs) of receiver and angles of departure (AoDs) of transmitter respectively. $\mathbf{a}_{\mathrm{R}}(\phi_p^R, \theta_p^R)$ and $\mathbf{a}_{\mathrm{T}}(\phi_p^T, \theta_p^T)$ are the normalised receive and transmit array response vectors. If λ and d stand for signal wavelength and spacing between antennas respectively, the array response vector for a uniform linear array (ULA) consisting of M antenna elements is given as follows [19]

$$\mathbf{a}(\phi) = \frac{1}{\sqrt{M}}\left[1, e^{j\left(\frac{2\pi}{\lambda}\right)d \sin\phi}, \ldots, e^{j(M-1)\left(\frac{2\pi}{\lambda}\right)d \sin\phi}\right]^T \quad (4)$$

Approximate Bit Error Rate Expression
BER is defined as the ratio of number of bits received in error to the total number of bits received in a digital communication system. It can occur due to channel noise, interference, hardware malfunctions or synchronisation issues in the communication system. In this section, we derive an approximate expression of BER for estimating the upper bound of error performance for the downlink of mmWave massive MIMO systems.

After being processed by the receiver combiners, signal $\tilde{\mathbf{y}}$ is applied to the detection stage to estimate the transmitted data signal vector. The data detection [21] at the receiver is performed by adopting the minimum distance detection technique as shown below.

$$\hat{\mathbf{s}} = \arg\min_{\mathbf{s}\in\mathbb{Q}} ||\tilde{\mathbf{y}} - \mathbf{Ts}||^2 \quad (5)$$

where $\hat{\mathbf{s}}$ is the estimated data symbol vector corresponding to the transmit symbol vector $\mathbf{s}$ and $\mathbf{T} = \mathbf{W}_{\mathrm{BB}}^H\mathbf{W}_{\mathrm{RF}}^H\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$. We assume that the elements of data vector $\mathbf{s}$ are obtained from a constellation $\mathbb{Q}$. An error takes place when $\hat{\mathbf{s}}$ is not same as $\mathbf{s}$. This happens under the following condition.

$$||\bar{\mathbf{y}} - \mathbf{Ts}||^2 > ||\bar{\mathbf{y}} - \mathbf{T}\hat{\mathbf{s}}||^2 \quad (6)$$

In other words, data vector $\mathbf{s}_p$ is erroneously detected as $\mathbf{s}_q$ i.e., a pairwise error event occurs when

$$\left\|\bar{\mathbf{y}} - \mathbf{T}\mathbf{s}_p\right\|^2 > \left\|\bar{\mathbf{y}} - \mathbf{T}\mathbf{s}_q\right\|^2 \quad (7)$$

$$\Rightarrow R\{\boldsymbol{\delta}_{pq}^H\tilde{\mathbf{n}}\} > \frac{\boldsymbol{\delta}_{pq}^H\boldsymbol{\delta}_{pq}}{2} \quad (8)$$

where $\tilde{\mathbf{n}} = \mathbf{W}_{\mathrm{BB}}^H\mathbf{W}_{\mathrm{RF}}^H\mathbf{n}$ is the coloured Gaussian noise after combining and $\boldsymbol{\delta}_{pq} = \mathbf{T}(\mathbf{s}_p - \mathbf{s}_q)$. Then, $R\{\boldsymbol{\delta}_{pq}^H\tilde{\mathbf{n}}\}$ has Gaussian distribution with zero mean and covariance $\frac{\boldsymbol{\delta}_{pq}^H\mathbf{R}_n\boldsymbol{\delta}_{pq}}{2}$ for large number of antennas at the receiver. $\mathbf{R}_n$ represents the noise covariance matrix at the output of the receiver combiners and is given as $\mathbf{R}_n = \mathbb{E}\{\tilde{\mathbf{n}}\tilde{\mathbf{n}}^H\} = \sigma_n^2\mathbf{W}_{\mathrm{BB}}^H\mathbf{W}_{\mathrm{RF}}^H\mathbf{W}_{\mathrm{RF}}\mathbf{W}_{\mathrm{BB}}$. Therefore, the pairwise error probability in this scenario can be evaluated as

$$P(\mathbf{s}_p \to \mathbf{s}_q) = Q\left(\sqrt{\frac{(\boldsymbol{\delta}_{pq}^H\boldsymbol{\delta}_{pq})^2}{2\boldsymbol{\delta}_{pq}^H\mathbf{R}_n\boldsymbol{\delta}_{pq}}}\right) \quad (9)$$

Using the probability of a union of events as the upper bound, the BER is bounded as follows

$$BER_{upper} = g\sum_{p=1}^{N}\sum_{q\neq p}^{N} d_{pq}\,\mathbb{E}\left\{Q\left(\sqrt{\frac{(\boldsymbol{\delta}_{pq}^H\boldsymbol{\delta}_{pq})^2}{2\boldsymbol{\delta}_{pq}^H\mathbf{R}_n\boldsymbol{\delta}_{pq}}}\right)\right\} \quad (10)$$

where $g = (N\log_2 N)^{-1}$, N being the number of all possible transmit symbol vectors. The Hamming distance between symbol vectors $\mathbf{s}_p$ and $\mathbf{s}_p$ is denoted by d_{pq}. Thus, BER expression for the mmWave system can be approximately written as

$$BER_{approx} \cong BER_{upper} \quad (11)$$

The derived BER expression is independent of the modulation, precoding and combining technique applied to the mmWave system.

Low Complexity Hybrid Precoder (LC-HP) Design
In this section, we present low-complexity hybrid precoder and combiner design which maximises the achievable spectral efficiency (SE) given by

$$SE = \log_2\left(\left|\mathbf{I}_{N_{\mathrm{S}}} + \frac{\rho}{N_{\mathrm{S}}}\mathbf{R}_n^{-1}\mathbf{W}_{\mathrm{BB}}^H\mathbf{W}_{\mathrm{RF}}^H\mathbf{H}\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\mathbf{F}_{\mathrm{BB}}^H\mathbf{F}_{\mathrm{RF}}^H\mathbf{H}^H\mathbf{W}_{\mathrm{RF}}\mathbf{W}_{\mathrm{BB}}\right|\right) \quad (12)$$

The objective is to design the precoders $(\mathbf{F}_{\mathrm{RF}}, \mathbf{F}_{\mathrm{BB}})$ and combiners $(\mathbf{W}_{\mathrm{RF}}, \mathbf{W}_{\mathrm{BB}})$ that maximise the SE of the mmWave system. Due to constant magnitudes of analog precoder and combiner, the optimisation problem is con-convex one, and hence is hard to optimise. In order to reduce the difficulty level of the design problem, decoupled design approach is followed wherein precoders are designed firstly assuming that receiver can decode perfectly. The precoders thus designed are then used to design the receiver combiners. In order to design hybrid precoders, Frobenius distance between the optimal precoder and the hybrid precoder $\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}$ is minimised i.e.,

$$\arg\min_{\mathbf{F}_{\mathrm{BB}}, \mathbf{F}_{\mathrm{RF}}} \left\|\mathbf{F}_{\mathrm{opt}} - \mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}\right\|_F \quad \text{subject to} \begin{cases} ||\mathbf{F}_{\mathrm{RF}}\mathbf{F}_{\mathrm{BB}}||_F^2 = N_{\mathrm{S}} \\ \mathbf{F}_{\mathrm{RF}} \in \boldsymbol{\mathcal{F}}_{RF} \end{cases} \quad (13)$$

where $\mathbf{F}_{\mathrm{opt}}$ is the capacity optimal precoder for the SU-MIMO system under study and $\boldsymbol{\mathcal{F}}_{RF}$ denotes the set of possible analog precoders with constant magnitudes. The optimal precoder is obtained by performing the singular value decomposition (SVD) of channel $\mathbf{H}$ as follows

$$\mathbf{H} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H \quad (14)$$

where, $\mathbf{U} \in \mathbb{C}^{N_R \times N_R}$ and $\mathbf{V} \in \mathbb{C}^{N_T \times N_T}$ are the unitary matrices, whose columns represent the left and right singular vectors of the channel $\mathbf{H}$ respectively. $\mathbf{\Sigma} \in \mathbb{C}^{N_R \times N_T}$ is a diagonal matrix with singular values of $\mathbf{H}$ arranged in descending order along its diagonal. Matrices $\mathbf{V}$ and $\mathbf{U}$ can be expressed as $\mathbf{V} = [\mathbf{V}_1 \ \mathbf{V}_2]$, and $\mathbf{U} = [\mathbf{U}_1 \ \mathbf{U}_2]$, where $\mathbf{V}_1 \in \mathbb{C}^{N_T \times N_S}$ and $\mathbf{U}_1 \in \mathbb{C}^{N_R \times N_S}$ contain the first N_S columns of $\mathbf{V}$ and $\mathbf{U}$ respectively. Then, optimal precoder $\mathbf{F}_{opt} = \mathbf{V}_1$ and optimal combiner $\mathbf{W}_{opt} = \mathbf{U}_1$. This means transmission (reception) along the first N_S right (left) singular vectors of $\mathbf{H}$ will maximise the SE of the system. This is so because by using $\mathbf{V}_1$ and $\mathbf{U}_1$ as precoder and combiner respectively, a SU-MIMO channel can be converted into a set of N_S non-interfering parallel channels. Due to structural similarity between the transmit array response vectors and the columns of the analog precoder (both have constant magnitude phase shifters elements), the columns of the analog precoder $\mathbf{F}_{RF}$ can be taken from the set of array response vectors at the transmitter. Hence, optimisation problem can be reformulated as

$$\begin{aligned} &\arg \min_{\mathbf{F}_{BB}, \mathbf{F}_{RF}} \left\| \mathbf{F}_{opt} - \mathbf{F}_{RF}\mathbf{F}_{BB} \right\|_F \\ &\text{subject to} \begin{cases} \|\mathbf{F}_{RF}\mathbf{F}_{BB}\|_F^2 = N_S \\ \mathbf{F}_{RF}(:, p) \in \{\mathbf{a}_T(\phi_p^T, \theta_p^T), \forall p\} \end{cases} \end{aligned} \quad (15)$$

Out of N_P array response vectors at the transmitter, those L_T vectors (note that $\mathbf{F}_{RF}$ has L_T columns) which have maximum similarity (in decreasing order) with the optimal precoder are selected as columns of $\mathbf{F}_{RF}$ in a single step. This is done by taking projections of all transmit array response vectors along the optimal precoder and then selecting the vectors with maximum projection as the column vectors of $\mathbf{F}_{RF}$. Afterwards, $\mathbf{F}_{BB}$ is designed to minimise inter-stream interference using least square solution in digital domain i.e.,

$$\mathbf{F}_{BB} = \mathbf{F}_{RF}^{\dagger}\mathbf{F}_{opt} = (\mathbf{F}_{RF}^H\mathbf{F}_{RF})^{-1}\mathbf{F}_{RF}^H\mathbf{F}_{opt} \quad (16)$$

The hybrid combiner $\mathbf{W}_{RF}\mathbf{W}_{BB}$ at the receiver is designed in the same way by minimising the Frobenius distance of hybrid combiners from the optimal combiner. Similar to precoder design, the columns of $\mathbf{W}_{RF}$ are taken from amongst the set of array response vectors at the receiver following the same approach. Hence, this method adopts non-iterative design approach, therefore offers significantly reduced computational complexity.

The complexity of the LC-HP scheme and OMP-based hybrid precoding is $O(N_S^2(N_T + N_R) + N_P N_T N_S + L_T^3 + 2L_T^2 N_T + L_T N_T N_S)$ [3] and $O\left(N_S^2(N_T + N_R) + L_T N_P N_T N_S + \frac{1}{4}L_T^2(L_T+1)^2 + \frac{1}{3}N_T L_T(L_T+1)(2L_T+1) + N_T N_S L_T(L_T+1)\right)$ [22] respectively. In Tab. 1, computational complexity (number of complex multiplications) of the LC-HP method is compared with OMP-based method for various MIMO configurations when $N_S = 4$ data streams are transmitted, $L_T = 5$ RF chains are used at the BS and there are $N_P = 10$ propagation paths between the BS and MS. It can be seen that LC-HP technique achieves around 71% less computational complexity than OMP-based method under the mentioned MIMO setups.

Table 1. Complexity comparison of LC-HP and OMP-based hybrid precoding techniques.

$N_T \times N_R$	Complexity of LC-HP	Complexity of OMP-based method	Percentage complexity reduction for LC-HP relative to OMP-based method
32×16	4413	14753	70.09
64×16	8445	29025	70.90
128×16	16509	57569	71.32
256×16	32637	114657	71.54
256×32	32893	114913	71.38
256×64	33405	115425	71.06

2. Simulation Results

In the remaining part of the paper, the BER of the SU mmWave massive MIMO systems adopting LC-HP method is evaluated and analysed using analytic result in Eq. 11 and simulations. The error performance achieved with digital precoding is considered optimal. In all simulations, 16-QAM modulation is assumed. $N_S = 4$ data streams are transmitted from the BS to MS. Both ends of the link have equal number of RF chains i.e. $L_T = L_R = 5$. The antenna elements are arranged as ULA and spaced half wavelength apart. The carrier frequency is 28 GHz. It is assumed that there are $N_P = 5$ propagation paths out of which one is LoS path. In mmWave channels, the gain of LoS path can be higher by up to 15 dB than non-LoS paths [23]. It is assumed that complex gain of the LoS path has zero mean and unity variance whereas the non-LoS path has zero mean and 0.1 variance i.e. the power of LoS path is 10 dB higher than the non-LoS paths. In all simulations 1000 data symbols are transmitted. AoAs and AoDs are uniformly distributed in $[-90°, 90°]$.

Fig. 2 compares the performance of LC-HP method with digital precoding in terms of achievable BER for various values of SNR when BS has $N_T = 256$ antennas and the MS has $N_R = 16$ antennas. Fig. 3 shows the BER achieved when $N_T = 128$ antennas and $N_R = 16$ antennas. These figures demonstrate that BER performance obtained by Eq. 11 and simulations matches to a large extent for both LC-HP method and digital precoding. The error performance improves for the given SNR as the number of BS antennas increases. BER also decreases as SNR increases for the given MIMO configuration. The LC-HP technique is capable of achieving close to optimal error performance. In Fig. 4, the BER performance of the LC-HP method is compared with OMP-based hybrid precoding technique for 128×16 and 256×32 MIMO system. The LC-HP method can achieve almost same error performance as achieved by the OMP-based method, which is highly computationally complex due to its iterative nature. For example, Fig. 5 shows the percentage error in BER with respect to optimal values obtained through simulations when $N_T = 128$ and $N_R = 16$. It can be seen that BER performance of LC-HP method is even better than OMP-based method at high SNR values. The performance gap between LC-HP technique and the optimal digital precoding is also small.

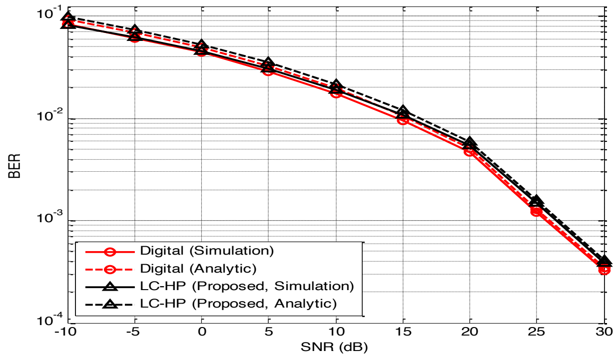

Fig. 2. BER versus receiver SNR for 256 × 16 mmWave massive MIMO system employing LC-HP method and digital precoding.

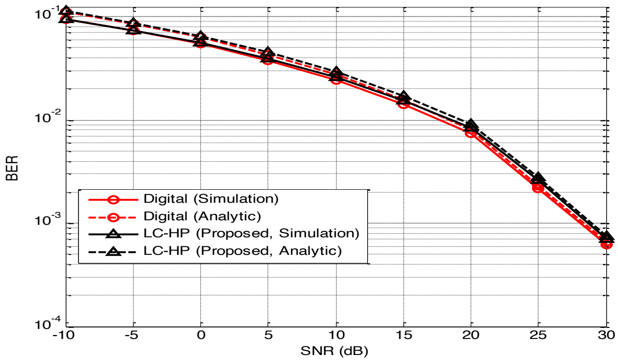

Fig. 3. BER versus receiver SNR for 128 × 16 mmWave massive MIMO system employing LC-HP method and digital precoding.

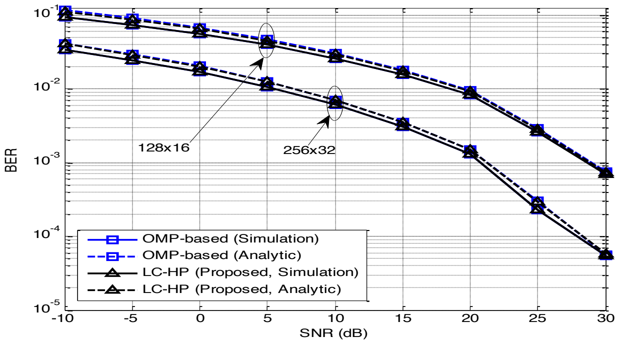

Fig. 4. BER versus receiver SNR for 128 × 16 and 256 × 32 mmWave massive MIMO system employing OMP-based hybrid precoding and LC-HP method.

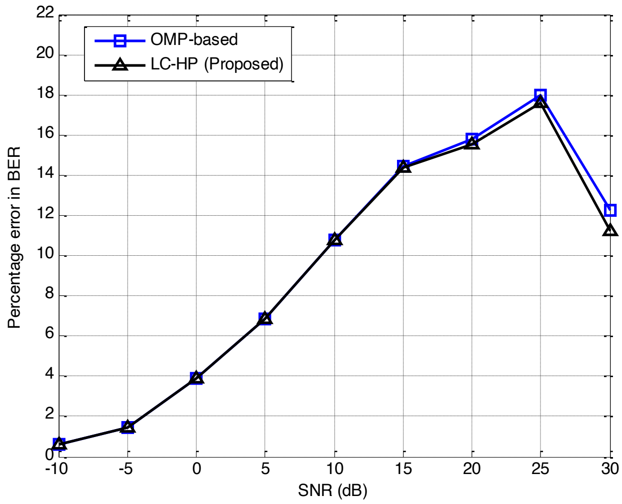

Fig. 5. Percentage error in BER from optimal values versus receiver SNR for 128 × 16 mmWave massive MIMO system. The performance has been obtained by simulations.

3. Conclusion

An approximate analytic expression of BER for evaluating the upper bound of error performance of mmWave massive MIMO systems is derived using minimum distance detection approach. The correctness of the expression is verified by comparing with simulation results. This paper also presents the design of hybrid precoders and combiners with low complexity for mmWave massive MIMO systems in single-user scenario. Decoupled design approach is adopted where precoders are first designed followed by the design of hybrid combiners. The numerical results indicate that the low-complexity design outperforms the high complexity OMP-based hybrid precoding technique at high SNR values.

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