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Integrating millimeter wave with hybrid precoding multiuser massive MIMO for 5G communication

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ABSTRACT

Nowadays, there has been growing interest in the Massive MIMO as a result of improving throughput by leveraging spatial freedom and array gain. It is equipped with millimeter wave (mm Wave) bands to resolve the high path-loss. It is known from the literature that iterated algorithms are usually used to attain the hybrid precoders to accomplish a specific optimization objective. Thus, the complexity remains high because each iteration may include singular value decomposition, the matrix inversion, and so on that motivates us to split the hybrid precoding and combining problem into sub-problems. The proposed solution is a multi-user Massive MIMO hybrid beamforming based on a convex optimization problem that is applied and solved for estimating the digital precoding to eliminate inter-user interference while using codebooks to select analog beamformers. It is apparent in the majority of cases; the proposed beamforming performance is higher than only-analog beamforming, single-user (no interference), the ZF precoding, the MMSE precoding, and the Kalman precoding where the full digital solution is a considerable as the benchmark point with different scenarios due to the reduction of user interference. Thus, there is no consideration for complicated operations such as SVD or inversion matrices as well as no need for data estimation. Our proposed solution can serve a large number of users simultaneously due to more directive gain by using numerous antennas at BS. Based on its less complexity and keeping performance, our solution can be recommended.

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1. INTRODUCTION

In recent years, researchers have shown a renewed interest in millimeter wave (mm Wave) bands for future cellular systems [1-3]. The shortage of sub-6 GHz spectrum resources means that conventional cellular systems suffer from a host of pitfalls such as the rapid growth in mobile information traffic, low latency, enormous connectivity, and low energy consumption in 2020 and beyond. The range between 3 and 300 GHz enables the access to wireless transmissions with large underused bandwidths and makes it easier to apply compact large antenna arrays due to its short wavelength [4-6], as detailed in Figure 1.

Massive Multiple-Input Multiple-Output (Massive MIMO) is a reliable technique, which improves throughput by leveraging spatial freedom and array gain [7]. To enable multi-gigabit data rates, the integration of mm Wave bands with multi-user Massive MIMO (MU-Massive MIMO) systems are a vital aspect [8]. Moreover, the large-scale antenna arrays for each Base Station (BS) and Mobile Station (MSs), as well as the precoding (beamforming), which contribute to the elimination of user's interference and achieve various benefits such as canceling out noise and fast fading through highly directional beamforming [9, 10]. On the other hand, small-cells such as micro-cells, femto-cells, and pico-cells that can combine mm Wave and Massive MIMO to avoid signal attenuation and achieve 3D beamforming [11].

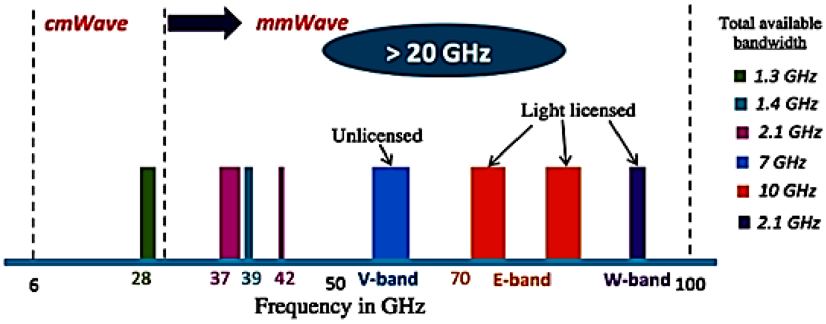

Figure 1. Mm Wave spectrum [6]

For mm Wave Massive MIMO systems, based on a literature perspective, a fully digital precoding solution where each antenna links to a dedicated RF chain that is known as an impractical solution for high frequency because of high costs and high power consumption [12, 13]. Although an analog precoding solution is less complicated with a phase shift that controls signal phases, the capacity cannot be considerably improved. As a result, the analog precoders perform less than the fully digital precoders [14].

In this context, a hybrid beamforming solution exploits analog beamformers in the RF domain and digital precoders in the baseband, which are considered as a promising solution to these challenges and enable us to take the advantages of both the solutions [15]. Most of the current research has tended to focus on single-user MIMO (SU-MIMO) schemes in the literature, although there are few studies on the hybrid beamforming for multi-user Massive MIMO (MU-Massive MIMO) schemes that can improve system capacity and spectral efficiency [11, 16-22].

The hybrid precoding algorithms require a perfect channel state information (CSI) through their design, although it is difficult in mm Wave MIMO systems due to a channel matrix measured based on the selection of analog beamformers at the baseband [23]. Many applications need the spectrum that ranges between 3 and 300GHz. The authors in [24] used Cognitive Radio Networks to avoid the lack of Spectrum. In [25], the authors proposed a mathematical model that requires the high carrier frequency for using a Wireless Video to monitor Transport Infrastructure. In [26], the authors designed a circuit to enhance gain and reduced power consumption used in different wireless systems. The authors in [27] offered a Black Spots Warning Application that reduces crashes at black spots.

For mm Wave MU-Massive MIMO systems, there are several previous studies. The authors in [28, 29] suggested the analog precoding solutions with low-cost phase shifters as an alternative to the full-digital precoding solution. However, it has limited ability to handle inter-user interference. Authors in [30] proposed hybrid beamforming based on a Kalman criterion to eliminate inter-user interference. In [31], the authors used a zero-forcing (ZF) precoding solution with the proposed channel estimation algorithm. Authors in [32, 33] developed hybrid beamforming based on a minimum mean square error (MMSE). In [34], the authors developed a feedback mechanism that would allow the BS to produce a sophisticated RF precoding structure. In [2], the authors Investigated the hybrid precoding and combining based on the perfect knowledge of the CSI, while a singular value decomposition (SVD) is used to achieve the analog combiner of each user while the Frobenius matrix of the matrix is minimized to complete the analog and digital precoding through the alternating optimization approach. In [35], the authors proposed the use of the alternative MMSE-based a generalized Eigen-decomposition (GEVD) to achieve analog beamforming, while a Karush-Kuhn-Tucker (KKT) is used to optimize digital precoding. In [36], the authors used metrics via the optimization approach to achieve analog and digital precoding. Finally, the authors in [37] suggested an iterative algorithm using the KKT-based penalty dual decomposition technique.

In comparison, the two applications, the specifications, and needs of each application for their regular activity should be determined and then compared [38]. Various measures and techniques must be adopted to minimize reasons and impacts to improve communication [39]. It is known from the literature that iterated algorithms are usually used to attain the hybrid precoders to accomplish a specific optimization objective. Thus, the complexity remains high because each iteration may include singular value decomposition, the matrix inversion, and so on.

The above reasons motivate us to split the hybrid precoding and combining problem into sub-problems. The proposed solution involves two phases: firstly, the analog beamforming and combining matrices are designed to obtain the maximum energy principle for single-user systems. Secondly, a convex optimization problem is applied and solved to estimate the digital precoding, which is used to eliminate inter-user interference. The novelty of this work can be summarized as:

- We form the channel matrix based on a collection of array response vectors with low feedback rate while using codebooks to select analog beamformers. After that, a convex optimization problem is applied and solved to estimate the digital precoding. Thus, there is no consideration for complicated operations such as SVD or inversion matrices while keeping performance.
- The Frobenius norm of the matrix includes only the analog precoding, analog combining, and channel matrix while there is no need for data estimation.
- Under the same conditions, our analytical and simulation findings show that proposed precoding achieves better spectral efficiency than other existing hybrids such as the ZF precoding [27], the MMSE precoding [21, 28], and the Kalman precoding [26].

2. RESEARCH METHOD

Notations: In this study, A and a are a matrix and a vector, while $|A|, \|A\|_F, A^T, A^H$ are its determinant, Frobenius norm, transpose, and Hermitian, respectively. I and E[.] denote the identity matrix and the expectation. NxM Is used to indicate (N×M) complex matrix.

2.1. System model

For the multi-user mmWave massive MIMO system, we consider the single BS and K users as illustrated in Figure 2, where the BS with N_{BS} antennas and N_{RF}^t RF chains that transmits N_S data streams to K users, each with N_{MS} antenna.

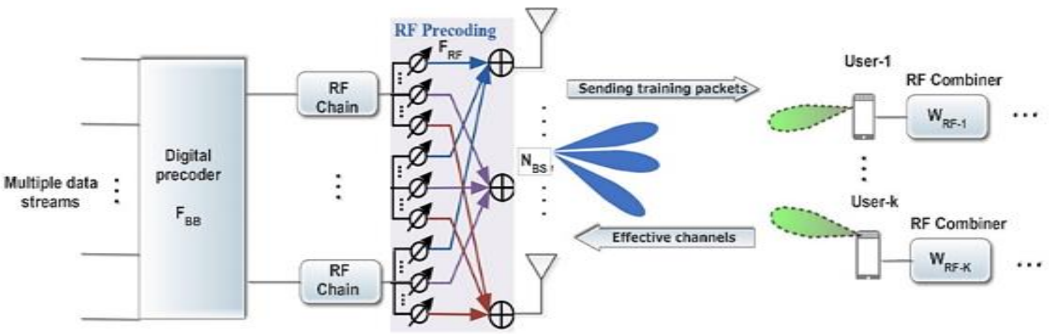

Figure 2. Proposed hybrid precoding system

At the BS side, the digital precoder matrix $F_{BB} \in N_{RF}^t \, x \, N_S$ digitally processes NS data streams followed by the analog beamforming matrix $F_{RF} \in N_{BS} \, x \, N_{RF}^t$ that exploits phase shifters to minimize energy consumption and costs, so that the BS transmits the final hybrid precoded signal to K users, that is where $X \in N_{BS} \, x \, 1$ denotes the transmitted vector and $S \in N_s \, x \, 1$ denotes the input baseband vector. Next, the received signal at user k becomes;

$$\mathrm{X} = F_{\mathrm{RF}} \sum_{\kappa=1}^{\mathrm{K}} F_{\mathrm{BB}} S \tag{1}$$

$$r_k = H_k F_{\mathrm{RF}} F_{\mathrm{BB}} S + n_k. \tag{2}$$

where $r_k \in \mathbb{C}^{N_S x 1}$ is the received vector, $H_k \in \mathbb{C}^{N_{MS} x N_{BS}}$ is the channel matrix, and $n_k \in \mathbb{C}^{N_{MS} x 1}$ is the Gaussian noise vector satisfying $E[n_k n_k{}^H] = \sigma^2 I_{N_S}$. At the receiver side, an analog combiner matrix $W_{\mathrm{RF}} \in \mathbb{C}^{N_{MS} \times N_{RF}}$ combines the received signal to estimate the processed data, given by;

$$\hat{s} = (W_{\mathrm{RF}})^H H_k F_{\mathrm{RF}} F_{\mathrm{BB}} S + (W_{\mathrm{RF}})^H n_k. \quad (3)$$

The path loss in the mmWave band is realistic. The mm-Wave MIMO channel model between the BS and the K users that has limited scatters with N_{ray} scatters in contrast to the low-frequency channel, that is;

$$H_k = \sqrt{\frac{N_{BS} + N_{MS}}{N_{ray}}} \sum_{\ell=1}^{N_{ray}} u_\ell u_{MS}(\theta_{MS,\ell})^H (u_{BS}(\varphi_{BS,\ell})) \quad (4)$$

where $\theta_{MS,1}$ and $\varphi_{BS,1}$ are Angles of Arrival (AoA) and Angles of Departure (AoD) respectively, and u_1 is complex path gains. The array response vector for linear arrays, which takes the form of where λ denotes the carrier wavelength, and $d = \lambda / 2$ that indicates the inter-antenna spacing.

$$u_{BS}(\varphi) = \frac{1}{\sqrt{N_{BS}}}\left[1, \ldots\ldots\ldots, e^{i(N_{BS}-1)\frac{2\pi}{\lambda} d \sin(\varphi)}\right] \quad (5)$$

$$u_{MS}(\theta) = \frac{1}{\sqrt{N_{MS}}}\left[1, \ldots\ldots\ldots, e^{i(N_{MS}-1)\frac{2\pi}{\lambda} d \sin(\theta)}\right] \quad (6)$$

2.2. Problem formulation

In the beginning, an effective feedback channel is a feasible solution to tackle huge training signal overhead. Then, the BS calculates the digital precoder that can eliminate inter-user interference. Finally, the problem of interest is to maximize the achievable rate of the system after calculating the analog beamforming, the effective channel and the digital precoding, which takes the form of;

$$H_{eff} = (W_{\mathrm{RF}})^H H_k F_{\mathrm{RF}} \quad (7)$$

$$R_K = \sum_{k=1}^{K} Log_2\left(1 + \frac{\frac{p_k}{N_S}\left|H_{k_{eff}} F_{\mathrm{BB}}\right|^2}{\frac{p_k}{N_S}\sum_{\substack{u=1 \\ k\neq u}}^{N_S}\left|H_{k_{eff}} F_{\mathrm{BBu}}\right|^2 + \sigma^2}\right) \quad (8)$$

2.3. Proposed hybrid beamforming

The quantized RF precoding vectors or the array response vectors produce codewords (columns) at the AoD. The proposed hybrid precoding exploits codebooks for selecting the analog beamforming/combining vectors. On the other hand, $\|F_{RF} F_{BB}\|_F^2$ indicates transmitted power constraint, that is ;

$$\begin{aligned} &\min_{F_{RF}, F_{BB}} E\|\hat{s} - s\|_F^2 \\ &\text{subject to } F_{RF} \in \{f_1, \ldots\ldots, f_m\} \\ &\|F_{RF} F_{BB}\|_F^2 \le P_K \end{aligned} \quad (9)$$

where P_K denotes the transmitted power.

For each direction, the BS performs training packets following by calculating the received signal strength indicator (RSSI). Then, each user estimates the effective channel in all direction to feed the BS. Figure 3 shows the transmission protocol. The convex optimization problem is applied and solved for approximating problem in (9) by using optimization tools.

$$\begin{aligned} &\min_{F_{RF}, F_{BB}} E\left\|I_{N_S} - H_{eff} F_{\mathrm{BB}}\right\|_F^2 \\ &\text{subject to } F_{RF} \in \{f_1, \ldots\ldots, f_m\} \\ &\|F_{RF} F_{BB}\|_F^2 \le P_K \end{aligned} \quad (10)$$

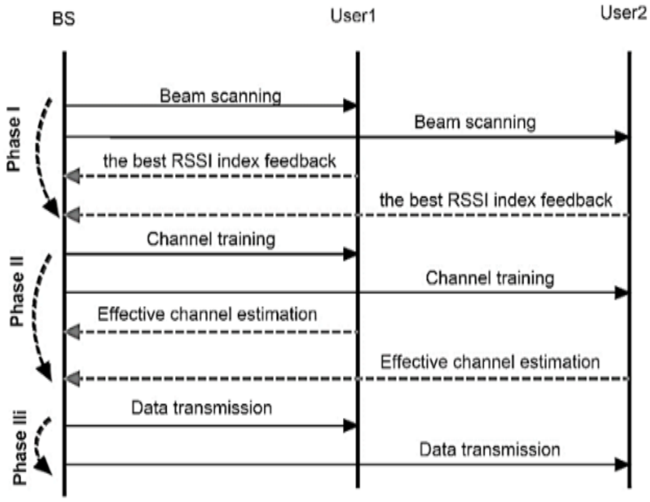

Figure 3. Transmission protocol between transmitter and the two user

Based on the above expression, there is no need for estimation data. At the first phase, the analog precoding and combining matrices are calculated to convexity the non-convex expression. Thus, the digital precoding is optimized. In this section, we compare the proposed solution with the previous works and the fully digital precoder (optimal case). The software package is Matlab for simulation and evaluation. Table 1 shows the simulation parameters.

Table 1. The simulation parameters

Parameters	Values
Number of UPA TX antennas	64,81,256
Number of UPA RX antennas	4,16
The number of users	4,8
The azimuth AoAs/AoDs	$[0; 2\pi]$
The elevation AoAs/AoDs	$[-\pi/2; \pi/2]$
The number of channel paths	1,10
Number of iterations	1000

3. RESULTS AND ANALYSIS

With the increase of SNR, there is no doubt that the proportional logarithmic relationship increases the spectral efficiency. Figure 4 demonstrates that only-analog beamforming is not adequate due to the overall restriction of one RF chain. Moreover, phase shifters can only be digitally controlled with quantized phases, which reduces the possibilities for advanced processing and leads to poor performance. Therefore, only one data stream can be handled, and a signal beam can be generated. While there are many RF chains used by the digital precoding. Consequently, there are several data streams to handle, and multiple beams are created from a single array simultaneously. As a result, our proposed solution exploits analog beamformers in the RF domain and digital precoders in the baseband that leads to increase data rates and spectral efficiency with diminishing the number of RF chains and processing multiple data streams.

The proposed solution includes system architecture with the number of RF chains at the BS and an RF chain per user under simulation configuration in the multipath condition. On the other hand, the others precoding performs better than the ZF precoding because they do not amplify the noise compared with the ZF precoding. The findings obtained by the proposed solution close to the single-user one that means our proposed can eliminate inter-user interference, as well as the number of antennas at BS and MSs that give a chance to reduce interference. It is explicit that the proposed algorithm performance is higher than hybrid precoding for Kalman, and MMSE by nearly 0.3b/s/Hz, and 0.7b/s/Hz, respectively, at SNR = 20dB. The reason for this is that our proposed solution split the hybrid precoding and combining problem into sub-problems. As a result, that leads to enabling better adjustment of the precoding baseband matrix, and others matrices.

Figure 5 indicates the simulation configuration with the number of antennas NBS = 81, NMS = 4, the number of users = 4, and the number of channel paths = 10 while Figure 6 refers NBS = 256, NMS = 16, the number of users = 4, and the number of channel paths = 10. With the increase in the number of antennas at BS and MS. As a result, that leads to increase the spectral efficiency, and data rate owning of more reuse channels bandwidths. In practice, more antennas are required at the BS than at the MS. The findings verify that the proposed solutions are being improved where the number of the antenna is more. According to the two figures below, the proposed algorithm performance is higher than hybrid precoding for Kalman, ZF, and MMSE. The reason for this is that the number of channel feedback bits and antennas are directly related.

Figures 7 and 8 indicates the simulation configuration with the number of channel paths = 10, the number of users = 8, and other different parameters. With the increase the number of users the ZF precoding is not sufficient owing to its multi-path failure, while the proposed algorithm provides the best spectral efficiency with the Kalman and the MMSE precoding. The reason for this the better adjustment of the precoding baseband matrix, and others matrices by proposed solution.

Figure 9 indicates the simulation configuration with the number of users = 8 and the number of antennas NBS = 64, NMS = 4. It shows that the different hybrid algorithms have a similar result for a single path scenario. The increasing number of paths means that their spectral efficiencies are shifted away from the fully digital curve, whereas the ZF precoding considers worse case due to its lack in exploiting multipath channel gains.

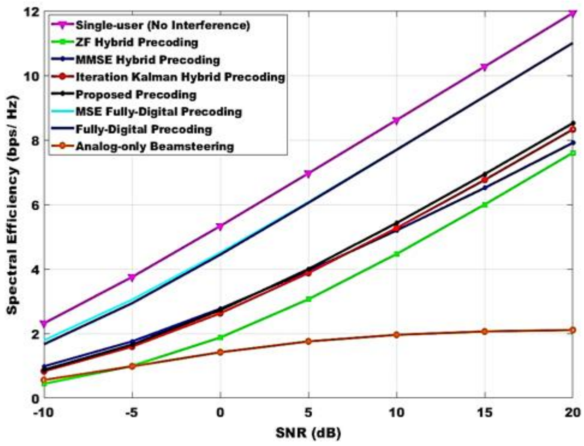

Figure 4. Various algorithms in a 64×4 mm Wave MIMO system with the number of users = 4 and the number of channel paths = 10

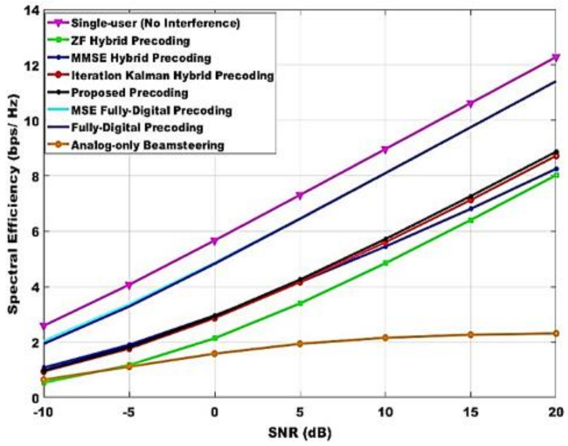

Figure 5. Different algorithms in an 81×4 the mm Wave MIMO system with the number of users = 4 and the number of the channel paths = 10

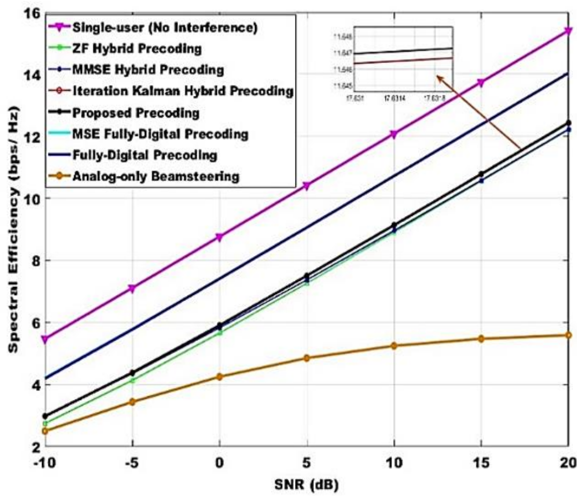

Figure 6. Different algorithms in a 256×16 the mm Wave MIMO system with the number of users = 4 and the number of the channel paths = 10

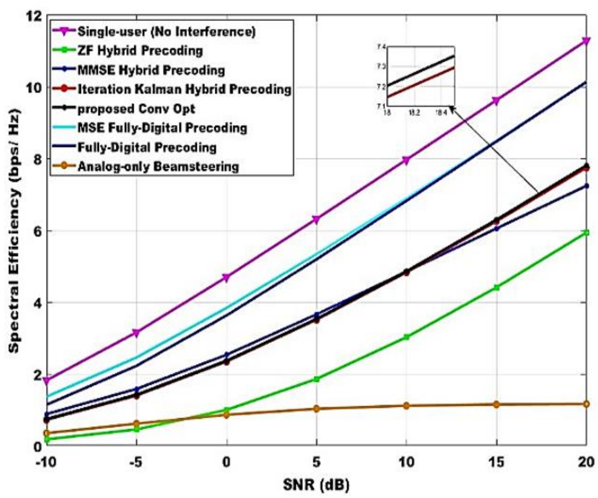

Figure 7. Different algorithms in a 64×4 the mm Wave MIMO system with the number of users = 8 and the number of the channel paths = 10

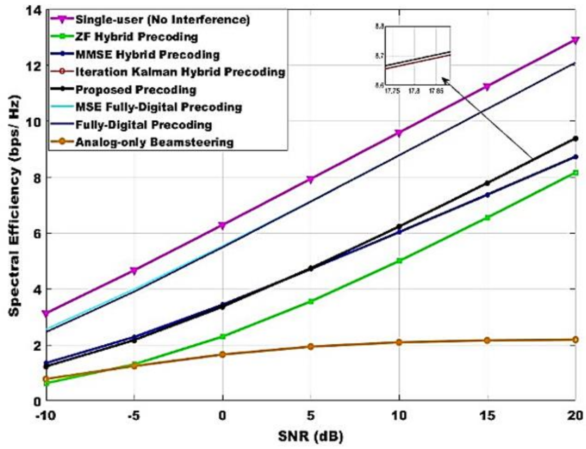

Figure 8. Different algorithms in a 256×16 mm Wave MIMO system with the number of users = 8 and the number of the channel paths = 10

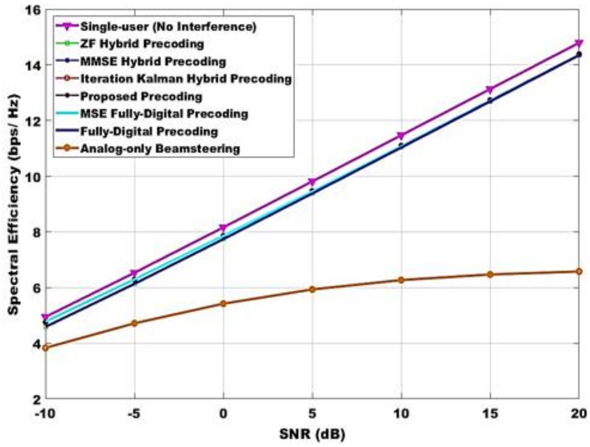

Figure 9. Different algorithms in a 256×16 mm Wave MIMO system withn the number of users = 8 and the number of channel paths = 1

It is apparent in the majority of cases; the proposed beamforming performance is higher than only-analog beamforming, single-user (no interference), the ZF precoding, the MMSE precoding, and the Kalman precoding where the full digital solution is a considerable as the benchmark point with different scenarios. Hybrid precoding has a higher coverage gain than analog beamforming, especially for massive numbers of BS antennas. Our proposed solution can serve a large number of users simultaneously due to more directive gain by using numerous antennas at BS. Based on its less complexity and keeping the performance, our solution can be recommended.

4. CONCLUSION

In this work, we have proposed a hybrid beamforming scheme based on the convex optimization problem for MU-Massive MIMO systems. The analog beamforming and combining are designed to obtain the maximum energy principle for single-use systems. After that, the convex optimization problem is used to estimate the digital precoding to eliminate inter-user interference. Under the same conditions, our analytical and simulation findings show that proposed precoding achieves better spectral efficiency than other existing hybrids. In the future, our work will be extended to joint hybrid precoding with user-beam scheduling to lower complexity more.

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