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Adaptive Hybrid Precoding for Reliable Multi-User mm-Wave MIMO Systems

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ABSTRACT: Wireless communication has revolutionized modern connectivity, with millimeter-wave (mm-Wave) technology emerging as a key component of next-generation networks due to its ability to deliver fast data rates and large capacity. Hybrid precoding is an important approach in mm-Wave MIMO systems for optimizing spectral efficiency, and it relies largely on accurate channel state information (CSI). The sparse characteristic of mm-Wave channels allows compressive sensing (CS) methods to be used for efficient channel estimation, considerably lowering pilot overhead and computational complexity. This study describes a novel hybrid precoding technique designed for reliable multi-user situations. The proposed two-stage framework uses SVD-based equal-gain transmission (EGT) for analog precoding and a Kalman filter for baseband precoding to effectively reduce inter-user interference. Numerical assessments show that the EGT-Kalman precoding method is comparable with standard strategies like zero-forcing (ZF) and MMSE precoding in terms of spectral efficiency. Furthermore, the pilot overhead is calculated, indicating the efficiency of the suggested technique in reducing training requirements while maintaining performance. This study highlights the promise of adaptive precoding techniques in developing mm-Wave communication systems by providing resilient performance in stable multi-user scenarios while tackling the challenges of sparse channel estimation.

1. INTRODUCTION

Millimeter-wave (mm-Wave) systems play a pivotal role in the 5G ecosystem, offering extensive channel bandwidth that significantly boosts data throughput and enhances network performance. Despite these benefits, mm-Wave signals face inherent challenges, including high susceptibility to path loss, limited range, and vulnerability to obstacles, all of which degrade signal quality. To address these challenges, beamforming emerges as a critical technique in mm-Wave systems [1, 2]. By directing signal energy toward specific directions, beamforming improves the received signal-to-noise ratio (SNR) and extends coverage.

This technique is particularly essential in mm-Wave massive MIMO (Multiple-Input Multiple-Output) systems, where it integrates three key components: channel estimation, precoders, and combiners. Hybrid beamforming, which divides signal processing tasks between the analog and digital domains, provides a cost-effective solution without sacrificing performance [3]. The design of precoding matrices in these systems relies heavily on accurate channel state information (CSI) [4, 5]. However, obtaining CSI in mm-Wave systems is challenging due to the large antenna arrays requiring extensive training and the low SNR levels prior to beamforming.

To tackle these challenges, compressive sensing (CS) techniques exploit the sparse nature of mm-Wave channels to reduce pilot overhead during channel estimation. In particular, matching pursuit algorithms are employed to estimate wideband mm-Wave sparse channels in the delay domain. This approach is especially beneficial in multiuser MIMO systems [6–8], where effective precoding is vital for system performance.

In multiuser MIMO systems, multiple users share the same frequency spectrum, leading to potential interference between transmitted signals. Precoding mitigates this issue by shaping transmitted signals to minimize cross-user interference. Accurate CSI enables the base station to understand the channel conditions for each user and adapt the precoding matrix accordingly. This ensures that signals intended for different users remain isolated, thereby enhancing overall system performance.

In [9], the authors introduce low-complexity hybrid precoding schemes tailored for multi-user massive MIMO systems. These schemes aim to address the high hardware and processing complexities inherent in massive MIMO systems while retaining the advantages of hybrid precoding. However, they encounter limitations related to the trade-off between performance and complexity. For instance, Zero-Forcing (ZF) beamforming, while effective at nullifying inter-user interference, may amplify noise, especially in low signal-to-noise ratio (SNR) scenarios. This leads to suboptimal performance in practical environments with varying SNR conditions. Furthermore, ZF beamforming depends on accurate channel state information (CSI), which is particularly challenging to acquire in high-mobility environments typical of massive MIMO systems.

In [10], the authors propose a Kalman-based framework for hybrid precoding, introducing an analytical error expression to simplify the Kalman algorithm and an iterative solution with

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manageable complexity. However, as the number of users or antennas increases, the complexity of the Kalman-based approach can escalate significantly. Additionally, the effectiveness of this method depends on accurate and up-to-date CSI. In practical mm-Wave systems, obtaining and maintaining such CSI can be difficult due to high mobility, rapid channel variations, and potential feedback delays.

The work in [11] presents an Orthogonal Matching Pursuit (OMP)-based algorithm to determine the Minimum Mean Square Error (MMSE) precoders and combiners. While this approach is effective, it involves substantial computational complexity, particularly in large-scale MIMO systems with many antennas and users. Moreover, the performance of hybrid MMSE precoding is heavily influenced by the accuracy of channel estimation, which remains a challenge in practical scenarios.

Given these challenges, this paper focuses on designing hybrid precoding techniques based on CSI for spatial multiplexing in large-scale mm-Wave MIMO systems. A novel hybrid precoding algorithm, termed as the Singular Value Decomposition Eigenvector Grouping and Tracking-based (SVD EGT-based) Kalman precoding, is proposed to address the challenge of maximizing system spectral efficiency. This algorithm integrates the radio frequency (RF) precoding matrix derived in the first stage, as described in [9], with a Kalman scheme implemented at the baseband level.

Additionally, the paper evaluates the performance of various precoding schemes, specifically: Zero-Forcing (ZF) as a baseband precoding technique combined with an RF precoder that enforces constant norm constraints. MMSE, as a baseband precoding technique, is also paired with an RF precoder that adheres to constant norm constraints.

This exploration highlights the trade-offs among complexity, performance, and practical feasibility in the design of hybrid precoding systems for large-scale mm-Wave MIMO applications.

1.1. Proposed Approach

A two-stage hybrid precoding method is proposed. The first stage performs RF analog combining, inspired by the single-user system framework, leveraging the Singular Value Decomposition (SVD)-based Equal Gain Transmission (EGT) principle. In the second stage, baseband precoding for multiuser systems is implemented using an iterative Kalman approach at the base station (BS) to minimize inter-user interference effectively.

By exploiting the sparse characteristics of mm-Wave channels, a low-complexity hybrid precoding algorithm is designed utilizing channel state information (CSI). The analysis includes evaluating the pilot overhead associated with compressive sensing (CS) techniques and the computational complexity of the proposed algorithm. Comparative assessments with existing precoding methods demonstrate the efficiency and reduced complexity of the new approach.

2. SYSTEM MODEL

To develop a system model for a stable or slowly varying channel multi-user system, we will outline a basic framework that addresses a general multi-user MIMO system. This section presents a mathematical model for mm-Wave channels, utilizing CSI to perform precoding. The model includes a novel EGT based Kalman precoding, as well as other precoding techniques such as Minimum Mean Square Error (MMSE) and Zero-Forcing (ZF).

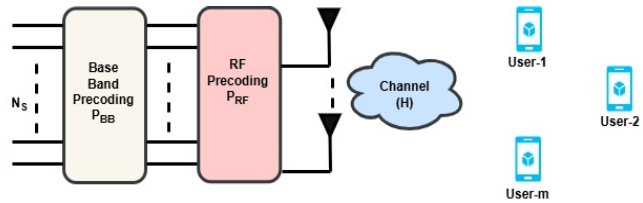

FIGURE 1. A multiuser millimetre wave hybrid system.

Figure 1 contains the RF precoding (P_{RF}), Base Band precoding (P_{BB}), number of streams (N_s), number of mobile station users MS-m, analog combiner (w_{RF}), and channel represent by H. The BS is equipped with N_t^{RF} RF chains; MS is equipped with N_t antennas and one RF chain. In this network, the BS communicates with each MS via one stream [12]. Then, the signal at the user's side, r, can be written as

$$r = HP_{RF}P_{BB}s + n$$

The received signal with interference

$$r = HP_{RF}p_{BBm}s + H\sum_{j\neq m}^{M} P_{RF}p_{BBj}s + n$$

The MS employs only analog combining w_{RF}, and after the combining process the estimated symbol of each MS can be expressed as

$$\begin{aligned} w_{RF}r &= w_{RF}\left(HP_{RF}P_{BB}s + n\right) \\ \hat{r} &= w_{RF}HP_{RF}P_{BB}s + \hat{n} \end{aligned}$$

The combining process with interference

$$\hat{r} = w_{RF}HP_{RF}p_{BB}s + w_{RF}H\sum_{j\neq m}^{M} P_{RF}p_{BBj}s + \hat{n}$$

2.1. mm-Wave MIMO Channel Model

The mm-Wave MIMO channel differs from conventional MIMO channels in several key ways. Firstly, the high path loss associated with mm-Wave frequencies causes significant performance degradation, which can be mitigated through beamforming techniques. Secondly, the closely spaced antenna arrays in mm-Wave systems lead to a highly correlated MIMO channel. Lastly, the sparse scattering environment of the mm-Wave channel results in a reduced-rank MIMO channel matrix [13–21].

This study gives the downlink channel to simulate with L scatters,

$$H = \sqrt{\frac{N_{BS}N_{MS}}{L}} \sum_{l=1}^{L} \alpha_l a_{MS}(\theta_l)\, a_{BS}^{H}(\emptyset_l)$$

where N_{BS} and N_{MS} are the numbers of antennas at the transmitter and the user side, respectively; L is the number of scatterings; α_l is the complex gain of l^{th} scattering; θ_l, $\emptyset_l$ are angles of departure (AoD) and arrival (AoA) corresponding to the l^{th} cluster; and $a_{MS}(\theta_l), a_{BS}^{H}(\emptyset_l)$ are the directional antenna gains at the transmitter and receiver antennas, respectively. The normalized antenna array vectors at the transmitter and the receiver, respectively, determine the beamforming directions. Here, in [16] the antenna arrays are in 1-D Uniform Linear Array (ULA) pattern with equally-spaced antennas. The 1-D ULA antenna array vector can be expressed by

$$a_{BS}(\emptyset_l) = \frac{1}{\sqrt{N}_{MS}}\left[1, e^{j\pi sin\emptyset}, \ldots, e^{j(N_{MS}-1)\pi \sin\emptyset}\right]^T$$

$$a_{MS}(\theta_l) = \frac{1}{\sqrt{N}_{BS}}\left[1, e^{j\pi sin\theta}, \ldots, e^{j(N_{BS}-1)\pi \sin\theta}\right]^T$$

2.2. SVD-Based EGT Analog Precoding

Equal Gain Transmission (EGT) for multiuser scenarios involves the simultaneous transmission of signals to multiple users in a way that each user's signal is given equal power across the transmission paths. Using EGT, the BS can transmit each user's signal with equal power across all available antennas, even if they are at different distances from the base station or experience different levels of interference and fading. In [9], EGT uses SVD scheme which improves the performance by doing the orthogonalization of the channel matrix. We consider the SVD of the channel matrix H as

$$H = U\Sigma V^H$$

In the SVD-EGT scheme, rather than fixing the phase-shift values based on the channel matrix H, they are determined using the conjugate transpose of the precoding matrix, V^H. The SVD-EGT approach begins by performing singular value decomposition (SVD) on the channel matrix H. Afterward, it fine-tunes the phase-shift values that are applied to the conjugate transpose of the right singular matrix, denoted as V^H. V^H can be rewritten as

$$V^H = \begin{bmatrix} v_{11} & \cdots & v_{1R} \\ \vdots & \ddots & \vdots \\ v_{K1} & \cdots & v_{KR} \end{bmatrix}$$

From the first column of the above matrix, determine the phase values of w_r in step-6. In particular, w_1 is determined by first computing $l1$-norms of v_{k1}, $k = 1, 2 \ldots K$ and determining the highest value among them. Mathematically, the equation $w_r \leftarrow e^{(-jv_{\pi(r)r})}$ will be written.

Here $\pi(r) \leftarrow \arg max_{i\epsilon I} \|v_{ir}\|_1$

SVD EGT algorithm

Step-1: $[\mathrm{U}, \Sigma, \mathrm{V}] = \mathrm{SVD}(\mathrm{H}, \mathrm{econ})$
for $\mathrm{r} = 1,2,3 \ldots, \mathrm{R}-1$ do
Step-2: if $\mathrm{mod}(\mathrm{r}, \mathrm{K}) = 1$
Step-3: Initializes $\mathrm{I} \leftarrow \{1,2,3 \ldots \ldots, \mathrm{K}\}$
Step-4: end if
Step-5: select the
$\pi(\mathrm{r})$as the index i that maximizes the $\|\mathrm{h}_{\mathrm{ir}}\|_1$
$\pi(\mathrm{r}) \leftarrow \arg\max_{\mathrm{i}\epsilon\mathrm{I}} \|\mathrm{v}_{\mathrm{ir}}\|_1$
Step-6: $\mathrm{w}_\mathrm{r} \leftarrow \mathrm{e}^{(-\mathrm{j}\theta)}$, $\theta = \mathrm{v}_{\pi(\mathrm{r})\mathrm{r}}$
Step-7: $\mathrm{I} \leftarrow \mathrm{I} - \{\pi(\mathrm{r})\}$
Step-8: end for

2.3. Kalman Base Band Precoding

Kalman precoding is a powerful technique that leverages the Kalman filter for dynamic channel estimation and adaptive signal transmission. It is particularly effective in environments with rapidly changing channel conditions, such as vehicular and mobile communications.

The mobile station (MS) determined that the signal is s_e using the training vector $s(n)$ at iteration n after the base station (BS) sent the signal denoted by s. The Kalman Filter algorithm minimizes the [17] mean squared error of the training vector between the estimated signal-s_e and the sent message signal-s, $\|s - s_e\|^2$.

$$min_{F_{RF}, F_{BB}} E\left\{\|s - s_e\|^2\right\}$$

$$s_n(n) = \left(w^H H P_{RF} P_{BB}\right) s(n) + n(n)$$

$$min_{P_{RF}, P_{BB}} E\left\{\|I - HP_{BB}(n|n-1)\|^2\right\}$$

Here H is the effective channel

$$P_{BB}(n|n) = P_{BB}(n|n-1) + K(n) E\left\{\text{diag}\left[e(n)\right]\right\}$$

Here $e(n)$ is the nth Kalman iteration error, $K(n)$ the gain of Kalman filter, and $e(n)$ the error between $s(n)$-$s_e(n)$. Then, the equation is

$$P_{BB}(n|n) = P_{BB}(n|n-1) + K(n) \frac{I - HP_{BB}(n|n-1)}{\|I - HP_{BB}(n|n-1)\|_F^2}$$

$$K(n) = R(n|n-1) H^H \left[HR(n|n-1) H^H + Q_n\right]^{-1}$$
$$R(n|n) = [I - K(n) H] R(n|n-1)$$

3. THE PROPOSED PRECODING COMPUTATIONAL COMPLEXITY

This section examines the computational complexity associated with the proposed hybrid precoding algorithm. The complexity of the proposed algorithm, as presented in Table 1, arises from two main components: the assignment of RF precoding and the computation of the baseband precoder. Consider the mm-Wave MIMO system with $N_t = 64$, $N_r = 16$, $M = 4$, $N_t^{RF} = 4$.

TABLE 1. Complexity of the algorithmic solutions.

Paper	Scheme	Mode	Analog BF	Digital BF	Channel estimation	Total complexity
Anna Vizziello [10]	Two stages of Kalman precoding	Multiuser	With Codebook Selection	Kalman precoding	Perfect CSI	$O(M\ W\ F\ N_R)$ $+O(N(M^3 + M^2 X N_R))$
Duy H. N. Nguyen [11]	MMSE Based precoding	Multiuser	Codebook-Based Analog BF	SVD-Based Digital BF	Perfect CSI	$O(KN_R^3) + O(N_R^3 N_{RF})$
Muhammad Hanif [9]	EGT precoding	Multiuser	EGT based precoding	ZF precoding	Perfect CSI	$O(N_t^3) + O(N_t^2 N_R)$
	Proposed precoding	Multiuser	SVD-EGT Based precoding	Kalman precoding	Estimated CSI with CS algorithms and Perfect CSI	$O(N_t^2 N_R + N(M^3 + M^2 N_R))$

Here Q_n is the noise $Q_n = \left(\frac{1}{SNR}\right) I$

Proposed Algorithm

RF precoding design: analog design for each user P_{RF}, and w_{RF}

BS and MS-m select $\acute{v}$, w so

$H = U\Sigma V^H$

BS sets $P_{RF} = [v_1 \ldots . v_m]$ and MS-m sets $w_{RF} = e^{(-jv_{\pi(r)r})}$

Base Band precoding design: multi user P_{BB}

MS-m estimate the $h_m^H = w_{RF}^H H_m P_{RF}$

MS − m claculates $h_m = \text{argmax}_{h_m \epsilon H} \|h_m^H h_m\|$

BS sets $H = H_e = [h_1 \ldots \ldots . . h_M]^H$

At BS for $n \leq N$ do:

$$e(n) = \frac{I - HP_{BB}(n|n-1)}{\|I - HP_{BB}(n|n-1)\|_F^2}$$

$$P_{BB}(n|n) = P_{BB}(n|n-1) + K(n)e(n)$$

$$K(n) = R(n|n-1)H^H[HR(n|n-1)H^H + Q_n]^{-1}$$

$$R(n|n) = [I - K(n)H]R(n|n-1)$$

$$P_{BB} = \sqrt{P}\frac{P_{BB}}{\|P_{RF}P_{BB}\|_F}$$

Performing Singular Value Decomposition (SVD) on the channel matrix H has a computational complexity of $O(N_t^2 N_R)$ where N_t and N_R are the number of transmitting antennas and number of receiving antennas. Since EGT relies on the right singular vectors V, it plays a crucial role in optimizing hybrid precoding. The key operations in Kalman filtering involve matrix multiplications and inversions. The hybrid precoding system consists of N_R receiving antennas and M users. Kalman Gain Calculation $K(n)$ involves a matrix inversion and multiplication, with a complexity of $O(M^3)$ for the inversion and $O(M^2 N_R)$ for the multiplications. The complexity of updating $F_{BB}\ (n \mid n)$ is $O(M^2 N_R)$. The overall complexity per iteration of the Kalman filter is approximately $O(M^3 + M^2 N_R)$. Suppose that the Kalman filter runs for N iterations. The total complexity of the Kalman-based baseband precoding would then be $O(N(M^3 + M^2 N_R))$. Total Complexity of Combined EGT and Kalman Precoding is $(N_t^2 N_R + N(M^3 + M^2 N_R)$.

4. SIMULATION RESULTS AND DISCUSSION

This section presents an analysis based on simulation of the proposed scheme. We find the pilot overhead of the applied CS algorithms and compare them in terms of NMSE vs pilot overhead (%). The performance of the proposed algorithm is compared with that of zero-forcing and MMSE hybrid precoding methods. Furthermore, we also provide the simulation results of the spectral efficiency as a parameter to evaluate the performance of the proposed hybrid precoding scheme with compressive sensing algorithms, which effectively describes the mm-Wave environment. Figure 2 illustrates the pilot overhead, defined as M/N, where M indicates the sparse channel dimension and N the dimension of the received signal. The OMP performed well with approximately 2.22% pilot overhead compared to Cosamp. At an NMSE performance level of -10 dB, the OMP algorithm achieves a pilot overhead of 23%, and Cosamp algorithm achieves a 30% pilot overhead. Figure 3 compares the three hybrid precoding solutions with the proposed Kalman precoding scheme. Besides, ZF and MMSE are included. The proposed EGT-Kalman-based precoding method was initially designed for a single-user system and later extended to a multi-user MIMO scenario. The proposed Kalman precoding demonstrates superior performance compared to the

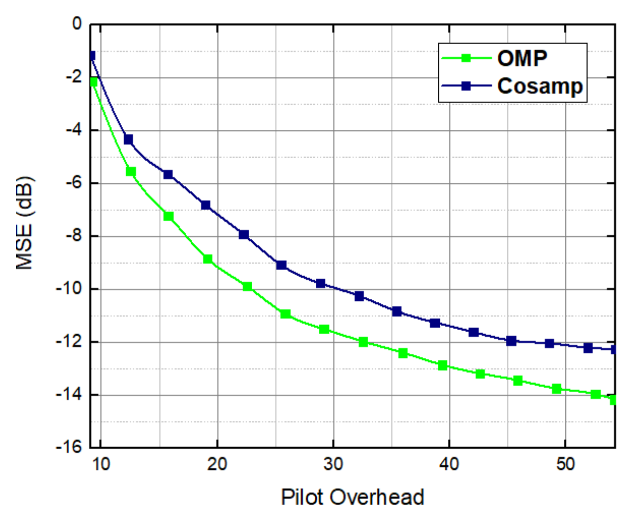

FIGURE 2. The NMSE versus the pilot overhead at SNR = 20 dB.

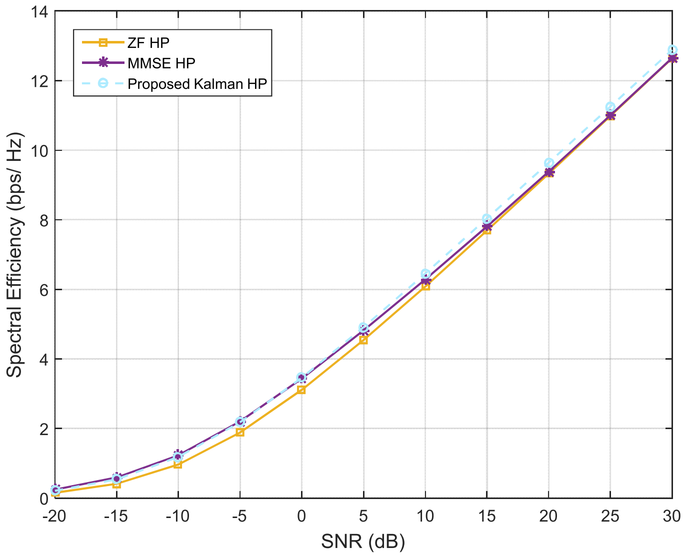

FIGURE 3. Comparison among hybrid precoding solutions: achievable rate varying SNR $= [-20, 30]$ dB with number of antennas $N_{BS} = 64$ number of MS antennas $N_{MS} = 16$ and number of users $M = 4$.

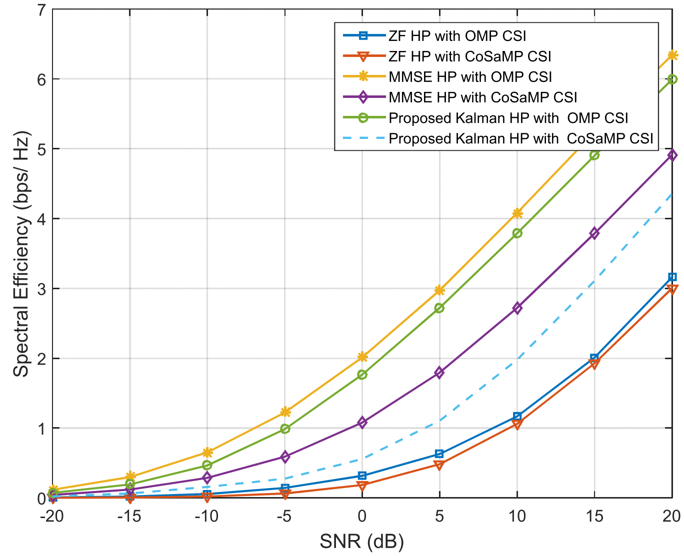

FIGURE 4. Comparison of hybrid precoding with CSI solutions: achievable rate varying SNR $= [-20, 20]$ dB with number of antennas $N_{BS} = 64$ number of MS antennas $N_{MS} = 16$ and number of users $M = 4$.

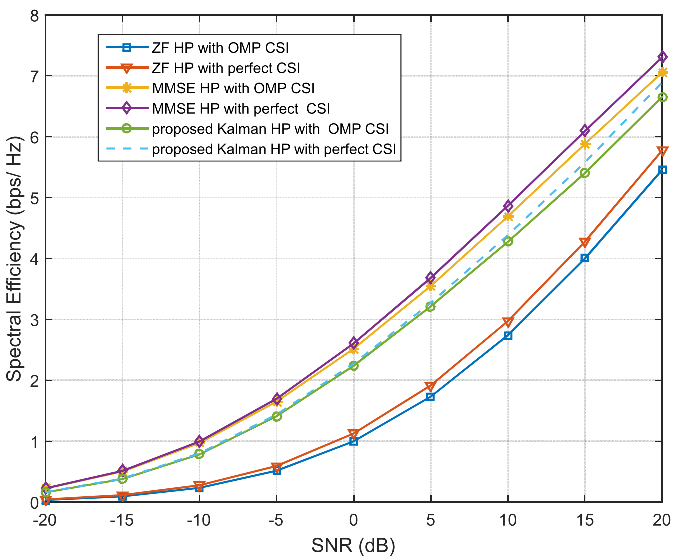

FIGURE 5. Comparisons of hybrid precoding with Perfect CSI solutions: achievable rate varying SNR $= [-20, 20]$ dB with number of antennas $N_{BS} = 64$ number of MS antennas $N_{MS} = 16$ and number of users $M = 4$.

other methods. Figure 4 compares the three hybrid precoding solutions including the proposed Kalman precoding scheme with the CSI. Initially, the proposed Kalman precoding shows better performance than others, but when these hybrid precoding schemes are applied with CSI, the results are shown in Figure 4. MMSE serves as the benchmark for SNR performance, and the proposed algorithm achieves performance closer to MMSE than conventional methods. In Figure 3, only hybrid precoding was performed, and Kalman precoding yielded the best results as shown. However, with CSI, MMSE achieved the highest spectral efficiency. In Figure 5, the perfect CSI is the bench mark from Figure 4. The CSI with OMP achieves the best results, followed by CoSaMP. A comparison of the three hybrid precoding solutions under both perfect CSI and OMP-based CSI estimation highlights that the proposed Kalman-based approach performs competitively, closely matching MMSE, while outperforming conventional methods. Perfect CSI and OMP with CSI produce nearly identical values at 0 dB.

5. CONCLUSION

By combining EGT for RF beamforming with Kalman filtering for digital precoding, the system can achieve a balance between computational complexity and performance, making it suitable for large-scale MIMO systems in mm-Wave communication. This combined approach is particularly effective in environments where high spectral efficiency and low bit error rates are crucial, while also managing the hardware limitations associated with mm-Wave systems. This paper applies OMP and Cosamp algorithms to estimate sparse channels, aiming to enhance performance. To assess these algorithms' effectiveness in practical channel estimation, we investigate multi-user downlink channel estimation for hybrid architecture mm-Wave massive MIMO systems. Simulation results reveal that OMP outperforms Cosamp in terms of mean squared error (MSE) and pilot overhead. Although the simulation results for the proposed multi-user precoding algorithm in mm-Wave massive MIMO systems show that it closely resembles the MMSE precoding technique in terms of spectral efficiency, when these precoding techniques were applied with based on CSI, the results were changed because the proposed Kalman based precoding algorithm requires accurate and up-to-date CSI to perform effectively. MMSE precoding with accurate CSI generally achieves better performance than ZF and EGT based Kalman precoding due to its simplicity and efficiency.

REFERENCES

[1] Uwaechia, A. N. and N. M. Mahyuddin, "A comprehensive survey on millimeter wave communications for fifth-generation wireless networks: Feasibility and challenges," *IEEE Access*, Vol. 8, 62 367–62 414, 2020.

[2] Rappaport, T. S., Y. Xing, G. R. MacCartney, A. F. Molisch, E. Mellios, and J. Zhang, "Overview of millimeter wave communications for fifth-generation (5G) wireless networks — With a focus on propagation models," *IEEE Transactions on Antennas and Propagation*, Vol. 65, No. 12, 6213–6230, Dec. 2017.

[3] Uwaechia, A. N., N. M. Mahyuddin, M. F. Ain, N. M. A. Latiff, and N. F. Za'bah, "On the spectral-efficiency of low-complexity and resolution hybrid precoding and combining transceivers for mmWave MIMO systems," *IEEE Access*, Vol. 7, 109 259–109 277, Aug. 2019.

[4] Hou, S., Y. Wang, and C. Li, "Uplink sparse channel estimation for hybrid millimeter wave massive MIMO systems by UTAMP-SBL," *Sensors*, Vol. 21, No. 14, 4760, 2021.

[5] Subitha, D., P. Poonkuzhali, I. Chandra, and P. V. Hemanth, "Hybrid precoding algorithm for massive MIMO system with imperfect channel knowledge," *Materials Today: Proceedings*, Vol. 80, 3235–3239, 2023.

[6] Gao, S., X. Cheng, and L. Yang, "Hybrid multi-user precoding for mmWave massive MIMO in frequency-selective channels," in *2020 IEEE Wireless Communications and Networking Conference (WCNC)*, 1–6, Seoul, Korea (South), May 2020.

[7] Björnson, E., L. Sanguinetti, J. Hoydis, and M. Debbah, "Optimal design of energy-efficient multi-user MIMO systems: Is massive MIMO the answer?" *IEEE Transactions on Wireless Communications*, Vol. 14, No. 6, 3059–3075, 2015.

[8] Alouzi, M., F. Al-Kamali, C. D'Amours, and F. Chan, "Direct conversion of hybrid precoding and combining from full array architecture to subarray architecture for mmWave MIMO systems," *IEEE Access*, Vol. 11, 35 457–35 468, 2023.

[9] Hsu, K.-N., C.-H. Wang, Y.-Y. Lee, and Y.-H. Huang, "Low complexity hybrid beamforming and precoding for 2D planar antenna array mmWave systems," in *2015 IEEE Workshop on Signal Processing Systems (SiPS)*, 1–6, Hangzhou, China, Oct. 2015.

[10] Hanif, M., H.-C. Yang, G. Boudreau, E. Sich, and H. Seyedmehdi, "Low-complexity hybrid precoding for multi-user massive MIMO systems: A hybrid EGT/ZF approach," *IET Communications*, Vol. 11, No. 5, 765–771, 2017.

[11] Vizziello, A., P. Savazzi, and K. R. Chowdhury, "A Kalman based hybrid precoding for multi-user millimeter wave MIMO systems," *IEEE Access*, Vol. 6, 55 712–55 722, 2018.

[12] Nguyen, D. H. N., L. B. Le, T. Le-Ngoc, and R. W. Heath, "Hybrid MMSE precoding and combining designs for mmWave multiuser systems," *IEEE Access*, Vol. 5, 19 167–19 181, 2017.

[13] Zhang, X. and F. Zhao, "Hybrid precoding algorithm for millimeter-wave massive MIMO systems with subconnection structures," *Wireless Communications and Mobile Computing*, Vol. 2021, No. 1, 5532939, Jun. 2021.

[14] Zheng, Z. and H. Gharavi, "Spectral and energy efficiencies of millimeter wave MIMO with configurable hybrid precoding," *IEEE Transactions on Vehicular Technology*, Vol. 68, No. 6, 5732–5746, 2019.

[15] Liu, Y., Q. Zhang, X. He, X. Lei, Y. Zhang, and T. Qiu, "Spectral-efficient hybrid precoding for multi-antenna multi-user mmWave massive MIMO systems with low complexity," *EURASIP Journal on Wireless Communications and Networking*, Vol. 2022, No. 1, 66, 2022.

[16] Boccardi, F., R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Communications Magazine*, Vol. 52, No. 2, 74–80, Feb. 2014.

[17] Abose, T. A., T. O. Olwal, and M. R. Hassen, "Hybrid beamforming for millimeter wave massive MIMO under multicell multiuser environment," *Indian Journal of Science and Technology*, Vol. 15, No. 20, 1001–1011, 2022.

[18] Rusek, F., D. Persson, B. K. Lau, E. G. Larsson, T. L. Marzetta, O. Edfors, and F. Tufvesson, "Scaling up MIMO: Opportunities and challenges with very large arrays," *IEEE Signal Processing Magazine*, Vol. 30, No. 1, 40–60, 2013.

[19] Larsson, E. G., O. Edfors, F. Tufvesson, and T. L. Marzetta, "Massive MIMO for next generation wireless systems," *IEEE Communications Magazine*, Vol. 52, No. 2, 186–195, 2014.

[20] Rappaport, T. S., S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5G cellular: It will work!" *IEEE Access*, Vol. 1, 335–349, May 2013.

[21] Rappaport, T. S., R. W. Heath Jr., R. C. Daniels, and J. N. Murdock, *Millimeter Wave Wireless Communications*, Pearson Education, London, U.K., 2015.