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Improving the Spectral Efficiency of Multiuser Multiple Antenna Millimeter Wave System Using Enhanced Kalman-Based Hybrid Precoder

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Abstract

Multipath fading remains a critical challenge in wireless communication systems, necessitating precoding schemes that are both flexible and robust under realistic transmission conditions. This study evaluated the performance of an enhanced Kalman-based hybrid digital precoding algorithm in a multipath environment with 10 paths and compared it with zero forcing (ZF), minimum mean square error (MMSE), and conventional Kalman hybrid digital precoding schemes reported in the literature. Using simulation-based analysis under varying numbers of base station (BS) antennas, the study assessed spectral efficiency as the primary performance indicator. The results showed that, at 64 BS antennas, the enhanced Kalman scheme outperformed ZF, MMSE, and Kalman precoding by 1.9711 bps/Hz, 1.7155 bps/Hz, and 1.11 bps/Hz, respectively. At 81 BS antennas, the corresponding performance gains were 1.7453 bps/Hz over ZF, 1.5344 bps/Hz over MMSE, and 0.9385 bps/Hz over Kalman. Similarly, at 256 BS antennas, the enhanced scheme achieved superior spectral efficiency by 1.4116 bps/Hz over ZF, 1.3324 bps/Hz over MMSE, and 0.9301 bps/Hz over Kalman. Overall, the findings demonstrate that the enhanced Kalman-based hybrid digital precoding algorithm consistently provides the highest spectral efficiency under identical multipath conditions, indicating improved data transmission performance over multipath communication channels. This study therefore contributes practical evidence for the application of enhanced Kalman-based precoding in wireless digital communication systems, with implications for achieving faster and more adaptable data transfer in realistic multipath environments.

Keywords: Enhanced Kalman Algorithm; Hybrid Digital Precoding; Multipath Fading; Spectral Efficiency; Wireless Communication Systems

INTRODUCTION

The dramatic increase in wireless data traffic around the world has resulted significant huge demands on existing wireless communication system. This condition will overwhelm existing infrastructure of 3Gpp and 4G networks. The use of a technology that includes the overlaying of small base stations (BSs) within the main network in terms of coverage demands can be a promising approach to achieving significant expansion and capacity of wireless network. One approach to facilitate and manage increase in data demand and transmit efficiency is by using massive Multiple Input Multiple Output (massive MIMO) system as in) where this technique was used to improve Bit-to-Error Rate (BER) performance, enhance channel capacity, and achieved near optimal sum rate (Muoghalu et al., 2021a, 2021b, 2021c).

The limited availability of spectrum has made the attention of experts in telecommunication to focus in the direction of millimeter wave (mmwave) frequencies that require miniature radiating antenna (Lin et al., 2019). This reduction of the size of antenna element absolutely fits the massive MIMO requirement and thereby making the use of these large-scale arrays a potential technology (Han et al., 2015; Khwandah et al., 2021). The use of mmwave bands extremely leverages massive-MIMO, because the decrease in wavelength allows packing large arrays of antennas at both transmit and receive ends (Mazetta et al., 2016). The frequencies assumed to be in the interval from 30 GHz and 300 GHZ are used to express mmwave, in order that the carrier wavelength can be measured between 10 mm to 1 mm (Borges et al., 2021). Since the arrangement of antennas often involve antenna spacing of one or half wavelength, this enables for inclusion of extra active antennas per unit of area.

At mmwaves, fully digital techniques are not feasible while purely analogue solutions suffer performance limitations (Vizziello et al., 2018). Several precoding schemes have been presented in literature to achieve spectral efficiency (in terms of in terms of achievable sum rate) in mm wave communication.

In mmwave communication, large antenna arrangements at both transmitting and receiving ends are required to improve spectral efficiency and to minimize high path loss. As a result of hardware constraints such as cost and design intricacy at mmwave frequencies, fully digital schemes are not feasible with large antenna configurations. Also, the use of only analogue techniques makes the mmwave to suffer severe limitations in performance. Many hybrid techniques that combine both digital and analogue models have been implemented to address this challenge. However, there is need to improve spectral efficiency to enhance data transmission capacity.

This work is designed to enhance spectral efficiency of mmwave communication under MU-MIMO scenario using hybrid method based on analogue and digital precoding solution.

METHODS

System model and description

A multiuser mmWave multiple antenna system is considered with single based station (BS) and K users as shown in Figure 1 in this work with a weighting factor enhanced Kalman hybrid precoding implemented. The figure is the multiuser multiple antenna system for mmwave frequency band in wireless communication presented in this work. As shown, the BS antennas are represented by N_{BS} and with N_{RF}^{t} RF chains, which transmits N_s multiple data streams to K number of users with N_{MS} number of mobile station (i.e. antenna).

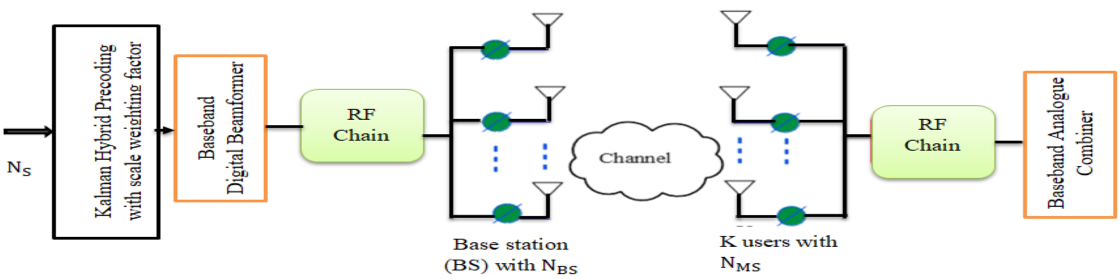

Figure 1. Kalman based hybrid precoding with scale weighting factor

As shown in Figure 3.2, the BS end consists of digital beamformer matrix $F_{DB} \in N_{RF}^{t} \times N_S$ that digitally processed the multiple data streams from the Kalman hybrid precoder. This is followed by the analogue beamforming matrix of RF chains $F_{RF} \in N_{BS} \times N_{RF}^{t}$ that takes advantage of the phase shifters to optimize the energy consumption and cost (Hussein & Khamiss, 2020a). This ensures that the final hybrid precoded signal is transmitted to the K users by base station.

Now, let $S \in N_s \times 1$ represents the input baseband vector (or signal i.e. matrix of the stream of data given by Equation (1) and $X \in N_{Bs} \times 1$ represents the transmitted vector matrix shown in Equation (2). The total transmitted signal to the K users is given by Equation (3). The r_kth received signal vector by kth user is defined in Equation (4).

$$S = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ \vdots \\ s_{N_s} \end{bmatrix} \tag{1}$$

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{N_{BS}} \end{bmatrix} \tag{2}$$

$$X = F_{RF} \sum_{\square=1}^{\square} F_{DB} S \tag{3}$$

$$r_k = H_k F_{RF} F_{DB} S + n_k \tag{4}$$

where r_k is received vector signal of k user, H_k is the channel matrix, and n_k is the Gaussian noise vector on the k user vector. At the receive end, the analogue combiner combines the received vector signal to estimate the processed data expressed by:

$$\hat{s} = (W_{RF})^H H_k F_{RF} F_{DB} S + (W_{RF})^H n_k \tag{5}$$

where $(W_{RF})^H$ is the conjugate transpose of the analogue combiner matrix. The channel model H_k between the base station and the K users for mmWave multiple antenna system has limited scatters with N_{ray} scatters unlike the low frequency channel and it is given by Hussein & Khamiss (2020a) and (2020b):

$$H_k = \sqrt{\frac{N_{BS}+N_{MS}}{N_{ray}}} \sum_{l=1}^{N_{ray}} \mu_l \, \mu_{MS}(\theta_{MS,l})^H (\mu_{BS}(\varphi_{BS,l})) \tag{6}$$

where $\theta_{MS,l}$ and $\varphi_{BS,l}$ are the complex path gains for angles of arrival and angles of departure. The array response vector for linear arrays usually expressed in terms of carrier wavelength considering the inter-spacing of antennas indicated by $d = \frac{\lambda}{2}$ at both base station (BS) and mobile station (MS) is given by Hussein & Khamiss (2020a):

$$u_{BS}(\varphi) = \frac{1}{\sqrt{N_{BS}}}\left[1, \dots, e^{j(N_{BS}-1)\frac{2\pi}{\pi}d\sin(\varphi)}\right] \quad (7)$$

$$u_{BS}(\theta) = \frac{1}{\sqrt{N_{MS}}}\left[1, \dots, e^{j(N_{MS}-1)\frac{2\pi}{\pi}d\sin(\theta)}\right] \quad (8)$$

The primary objective of precoders (or beamformer) is to cancel the effect of inter-user interference (IUI). Hence, the focus is to improve the achievable sum rate of the mmwave system after the analogue beamforming. Therefore, Equations (9) and (10) define the effective channel and the achievable rate of the K users (Hussein & Khamiss, 2020a):

$$H_T = (W_{RF})^H H_k F_{RF} \quad (9)$$

$$R_K = \sum_{K=1}^{K} = \mathrm{Log}_2\left[1 + R_n^{-1}(W_{RF})^H H_K F F^H H_K^H W_{RF}\right] \quad (10)$$

where $F = F_{RF}F_{DB}$ stands for the analog to digital precoder. The covariance matrix R_n is given by Shoukath *et al.* (2023):

$$R_n = \frac{1}{SNR}(W_{RF})^H W_{RF} \quad (11)$$

The signal to noise ratio (SNR) of the system is defined by Ali *et al.* (2023):

$$SNR = \frac{P}{N_s\sigma_n^2}(W_{RF})^H W_{RF} \quad (12)$$

where P denotes the total power transmitted and σ_n^2 stands for the noise power.

Hybrid beamforming based on Kalman technique

The concept of multiuser beamforming technique is that analogue combining matrix W_{RF} of each k^{th} user equipment (UE), which is a mobile station (MS) and the matrices of the hybrid analogue and digital precoding F_{RF} and F_{DB} at the BS are computed. By this, the hybrid mmwave beamforming matrix designed using Kalman-based technique is performed by minimizing the error given by Equation (13) in Equation (14) (Hussein & Khamiss, 2020a).

$$e(n) = \frac{s(n) - \hat{s}(n)}{\|s(n) - \hat{s}(n)\|_F^2} \tag{13}$$

$$\underset{F_{RF}, F_{DB}}{\text{minimize}} \; E\|s - \hat{s}\|^2$$

$$\text{subject to } \|F_{RF} F_{DB}\|_F^2 \leq P$$

$$F_{RF} \epsilon \{f_1, \ldots\ldots, f_L\} \tag{14}$$

where Equation (13) is error $e(n)$ at the n^{th} Kalman iteration. In Equation (14), the Kalman filter minimizes the sum of the mean square error $E\|s - \hat{s}\|^2$, which is given by the squared difference between BS transmitted signal s and the estimated signal $\hat{s}$ at the mobile stations (MSs) (which are the users equipment). The baseband digital beamforming matrix F_{DB} is considered state of the Kalman filter algorithm, while the analogue precoder (or precoding matrix) F_{RF} is considered the previous computed step of the algorithm. $\|F_{RF} F_{DB}\|_F^2 \leq P$ is the limit of the squared product of the analogue precoding matrix and the baseband digital beamforming matrix, which is equal to or less than P.

The state equation of the Kalman filter is defined by Vizziello et al. (2018):

$$F_{DB}(n|n) = F_{DB}(n|n-1) + K(n)E\{diag[e(n)]\} \tag{15}$$

where $K(n)$ is the Kalman gains at time instant n. The expression $E\{diag[e(n)]$ is the matrix of the error in Equation (13), which is using the expression defined by Vizziello *et al.* (2018):

$$E\{diag[e(n)]\} = \frac{I - \hat{H}_\epsilon F_{DB}(n|n-1)}{\|I - \hat{H}_\epsilon F_{DB}(n|n-1)\|_F^2} \tag{16}$$

where I is a unity matrix, and $\hat{H}_\epsilon$ is estimated total channel matrix. Therefore, Equation (15) can be re-expressed as:

$$F_{DB}(n|n) = F_{DB}(n|n-1) + K(n)\frac{I - \hat{H}_\epsilon F_{DB}(n|n-1)}{\|I - \hat{H}_\epsilon F_{DB}(n|n-1)\|_F^2} \tag{17}$$

In this work, Equation (17) was multiplied by using weighting scalar factor α that lies within the range of $1 \leq \alpha \leq 2$ with optimal value of 2 offering double digital baseband matrix.

Simulation parameters

The parameters of the millimeter wave multiuser multiple antenna system are listed in Table 1. Though, for the purpose of simulation in this work, some of the parameters (e.g. number of iterations) in the table will be varied including SNR.

Table 1. Simulation Parameters (Hussein & Khamiss, 2020a)

Parameter	Value
Number of uniform upper planar array (UPA) transmit antennas	64, 81, 256
Number of uniform upper planar array (UPA) receive antennas	4, 16
Number of users (or mobile stations)	4, 8
Azimuth angle of arrival/ angle of dispersion (AoAs/AoDs)	[0, 2*pi]
Elevation angle of arrival/ angle of dispersion (AoAs/AoDs)	[-pi/2, pi/2]
Number of channel paths	1, 10
Number of iterations	500, 1000

RESULTS

For the purpose of clarity which is offered among the spectral frequencies of the hybrid digital precoding algorithms with multiple paths scenario, this section will focus on the simulated results with number of paths = 10. Also, only results for 1000 iterations will be evaluated in this section with varied UPA Tx (i.e. BS antennas) under 4 users and 4 received antennas (UPA Rx). Figures 2 to 4 show the simulation curves for spectral efficiencies of the enhanced Kalman algorithm.

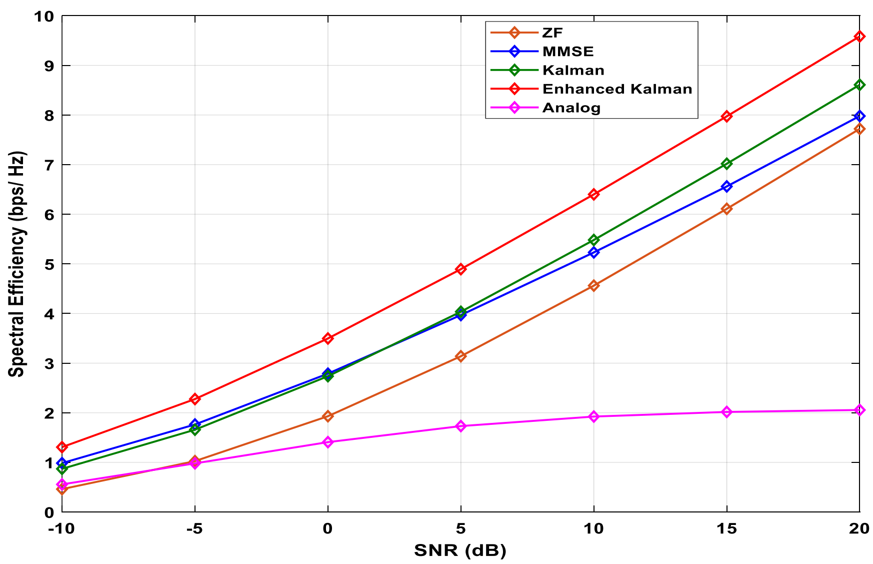

Figure 2. Performance of different algorithms including enhanced Kalman scheme (NP = 10, NI = 1000, UPA Tx = 64)

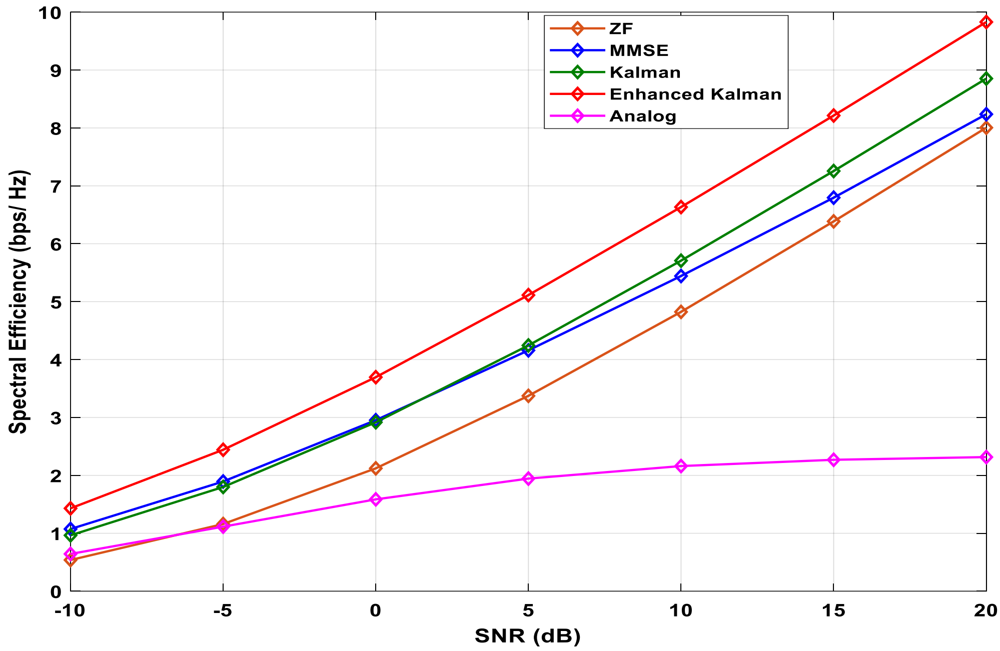

Figure 3. Performance of different algorithms including enhanced Kalman scheme (NP = 10, NI = 1000, UPA Tx = 81)

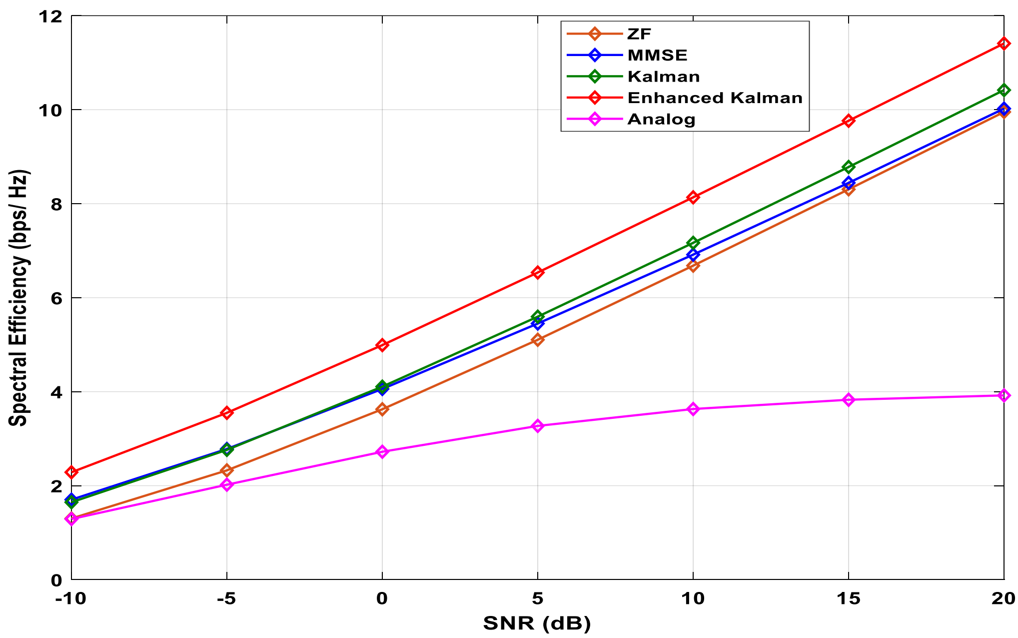

Figure 4. Performance of different algorithms including enhanced Kalman scheme (NP = 10, NI = 1000, UPA Tx = 256)

The value of the values of the spectral efficiency achieved by each precoding method is listed in Table 2.

Table 2. Spectral efficiency of different precoding schemes for mmwave at SNR = 20 dB

UPA TX	Spectral efficiency (bps/Hz)				
	ZF	MMSE	Kalman	Enhanced Kalman	Analog
64	7.6128	7.8684	8.4739	9.5839	1.9796
81	8.0842	8.2951	8.8910	9.8295	2.3459
256	9.9982	10.0774	10.4797	11.4098	4.0012

DISCUSSION

The use of different hybrid precoding schemes was to validate the effectiveness of the implemented large scale mmwave multiple antenna system. Simulations were carried out for different scenarios. The simulated results revealed that with increased number of iterations, the achieved spectral efficiency was improved. Then the number of paths was 10, reflecting multipath scenario. The results showed shifting in the spectral efficiency curves of the various hybrid precoding algorithms. This is due to multipath effect. However, the multipath case offered more practical experience considering the fact that in reality or in practice communication system encounters multipath fading issues. Hence, an enhanced Kalman based hybrid precoding was presented with multipath of 10 together with other previously implemented schemes in literature. The simulation results revealed that under the same conditions, the enhanced Kalman scheme offered highest spectral efficiency performance compared to the other algorithms.

The spectral efficiencies of different hybrid digital precoding algorithms including the enhanced Kalman algorithm presented in this work and the analog-only beamforming are shown in Figures 2 to 4. The simulated results indicated that the enhanced Kalman hybrid algorithm offered the best spectral efficiency compared to other schemes. Looking at Table 2, the improvement recorded by the enhanced Kalman hybrid precoding scheme over other schemes for different UPA Tx at SNR 20 dB are as follows. For UPA Tx = 64, the enhanced scheme showed better spectral efficiency performance than the other hybrid digital precoding schemes by 1.9711bps/Hz for ZF, 1.7155bps/Hz for MMSE, and 1.11bps/Hz for Kalman, respectively. With UPA Tx = 81, better performance in spectral efficiency was offered by the enhanced Kaman schemes against ZF, MMSE, and Kalman by 1.7453bps/Hz, 1.5344bps/Hz, and 0.9385bps/Hz, respectively. When the UPA Tx = 256, the enhanced algorithm outperformed the other schemes: ZF by 1.4116bps/Hz, MMSE by 1.3324bps/Hz, and Kalman by 0.9301bps/Hz, respectively.

CONCLUSION

The hybrid precoding algorithms achieved in high spectral efficiencies in single path scenario. This does not reflect the experience in wireless communication between base station and mobile users in practice. In multipath, the spectral efficiencies of the hybrid precoders dropped, which reflected the experience in reality wherein impact of multipath leads to fading over wireless channels. The hybrid precoders, ZF, MMSE, and Kalman showed similar results in single-path except the analog-only beamforming. However, with multipath, there is shift between the hybrid precoding systems. The introduction of the enhanced hybrid Kalman precoder improved the spectral efficiency higher above the original Kalman based scheme and other hybrid precoding algorithms with significant fraction. The larger the number of BS antennas the more the spectral efficiency achieved.

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