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ORIGINAL STUDY

Performance Evaluation of Millimeter Wave MIMO System Based on Hybrid Precoding and Combining

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Abstract

In the 5G wireless communication network, the mmwave used in most applications provides high data rates, low latency, high system capacity, and huge available bandwidths, but the multiuser case in the mmwave frequency range causes high path loss and reduced system performance. An efficient way to achieve high-performance large antenna arrays is hybrid precoding techniques that shall be applied at the base stations (BS) and mobile stations (MS). It is found that full digital precoding with large antenna arrays consumes high power and high hardware cost. This study presents low complexity hybrid precoding and combining techniques with a limited feedback system, based on the orthogonal matching pursuit (OMP) algorithm for both single and multiuser cases and compared its results with analog-only beamsteering. Moreover, the methods studied to describe hybrid precoding techniques are minimum mean square error (MMSE), zero forcing (ZF), and analog-only beamsteering. Simulation results show that the minimum mean square error (MMSE) precoders performed better than other hybrid precoding approaches. In addition, MMSE hybrid precoding/combining technique offers a higher spectral efficiency compared with analog-only beamsteering with large antenna arrays.

Keywords: Hybrid precoding/combining, Millimeter wave, MIMO, Minimum mean square error, Orthogonal matching pursuit

1. Introduction

Milimeter wave is one of the most important technologies in the communication field, which have frequencies ranging from 30 to 300 GHZ and short wavelengths from 10 mm to 1 mm (Samir et al., 2022). According to the advantage of short wavelength at mmwave frequencies, the poor characteristics associated with mmwave transmission such as severe path loss, atmospheric absorptions, and high penetration loss can address these problems by deploying a large number of antennas in a small region to achieve significant beamforming gain for controlling the interference among different users/cells (Mustafa et al., 2023). In a multiple input multiple output (MIMO) wireless communication system with mmwave the number of antennas can be increased to attain high spectral efficiency, effective spectrum sharing, and connectivity (Baranidharan et al.).

Despite the help of large antenna arrays, the severe propagation losses still limit mmwave communications to take place within short ranges. Fortunately, the coverage can be greatly extended with the help of relay nodes (Jiang et al., 2019).

To cancel the interferences between different data streams and decrease the complexity of the receiver, signals should be precoded before transmission (Jiang et al., 2019). In pure digital precoding, the processing for precoding is done using a digital signal processor, which provides greater flexibility with more degrees of freedom to implement efficient beamforming algorithms. The pure digital beamforming method requires a separate RF chain for each antenna element, which results in a complex architecture and high-power consumption. However, in the analog beamforming, the antenna weights can either be applied

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using time delay elements or equivalently phase shifting the signal before RF upconversion or after the upconversion stage (Ahmed et al., 2018). So, the best solution is hybrid analog/digital beamforming to overcome the limitations of pure digital or analog beamforming for a single user or a multiuser scenario. In addition, the advantage of the hybrid is the digital precoding in the transmitter and combiner at the receiver to reduce the precision of residual multi-stream in the analog (Vizziello et al., 2016).

Hybrid precoding was proposed (Vizziello et al., 2016; Kim et al., 2013; El Ayach et al., 2014; Le and Zhao, 2020), where Vizziello et al. (2016) proposed precoding solution for the MIMO system by calculating the RF precoding/combining matrix and designing the digital baseband precoder at the BS (Kim et al., 2013), presented the processing is divided between the analog and digital domains. The El Ayach et al. (El Ayach et al., 2014) study proposed a single-user MIMO with single-stream transmission based on a hybrid beamforming architecture at 28 GHz but not considered the effect of a multipath stream. Le and Zhao (2020) presented the method and analyses of the numerical results for the precoding algorithm for single-user mmWave MIMO systems and compared the spectral efficiency by different algorithms under the perfect and the imperfect channel state information (CSI). In Ref (Raisa et al., 2019) the author presented the comparison between hybrid precoding and optimal digital precoding solutions.

Vizziello et al. (Vizziello et al., 2016; Kim et al., 2013; El Ayach et al., 2014) studied only a single user, the single path for a limited number of antennas in BS (base station) and MS (mobile station) but was not interested in the effect of multipaths with a large number of antennas a BS and MS to improve the spectral efficiency of the system.

This paper considered the advantages of mmwave frequency ranges at the fifth-generation technology. and present the hybrid precoding and combining for MIMO wireless communication networks. In this system, precoding is applied to improve the performance, and after that studied the effect of zero forcing (ZF), minimum mean square error (MMSE) baseband precoding for a multiuser system to mitigate the inter-user interference.

The considered system was low complexity compared with fully digital precoding as shown in Fig. 1. A detailed description is in section II, which is applied for both single and multiple users, with either a single-path channel or a multipath channel to obtain the best of spectral efficiency. The performance of the considered system was analyzed with limited feedback, based on the concept of orthogonal matching pursuit (OMP). The result is compared with analog-only beamforming as described in detail in section V.

The main contribution of the paper can be summarized as: describing the hybrid precoding and combining system in order to make an effective balance between decreasing the hardware complexity and increasing the spectral efficiency.

This process can be applied in an outdoor environment with non-line-of-sight (NLOS) scattering medium in order to send multiple data streams through the channel.

Moreover, this paper provides a study of the three approaches for the mentioned process such as MMSE hybrid precoding, ZF hybrid precoding, and analog-only beamsteering. as well as studying the effectiveness of the number of users, number of paths, number of RF chain, and the number of antennas in BS and MS in order to evaluate the spectral efficiency on the mmwave MIMO system.

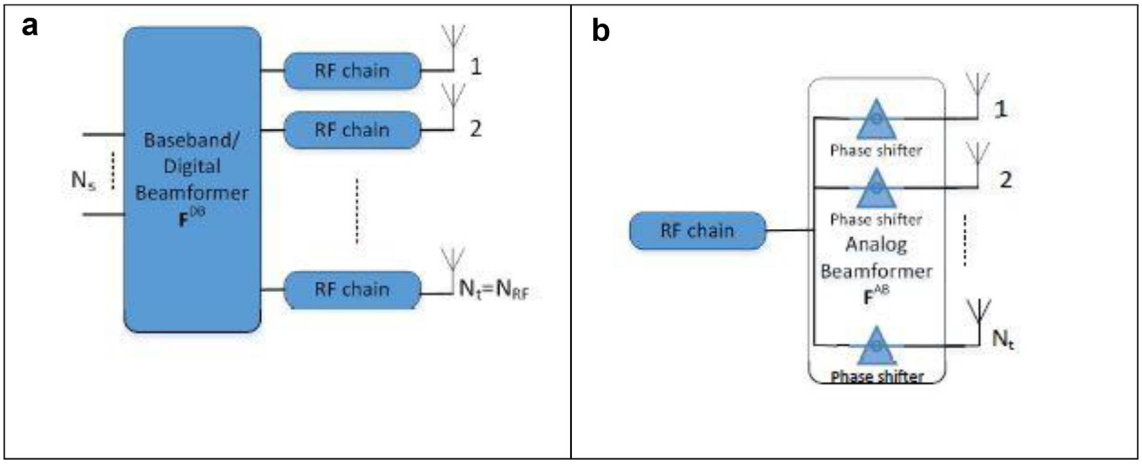

Fig. 1. (a) Block diagram of the digital precoding (Ahmed et al., 2018). (b) Block diagram of the analog-only precoding (Ahmed et al., 2018).

The organization of the paper comes as follows: Section II introduces the system model. Section III explains the channel model. Section IV describes the simulation results. Finally, Section V affords a conclusion and future work.

2. System model

The author in Ref (Ahmed et al., 2018) described the different precoding techniques, which has found that the fully digital processing is hard to realize at mmWave frequencies with wide bandwidths and large antenna arrays, because the baseband precoding/combining processing assumes that the transceiver dedicates an RF chain per antenna as shown in Fig. 1a. An analog precoding can be implemented using networks of phase shifters, but it causes high interferences as shown in Fig. 1b. In Fig. 2 (Li and Masouros, 2017), describes the hybrid precoding architecture which provides a flexible compromise between hardware complexity and system performance. The hybrid beamforming structure is proposed as an enabling technology to obtain the benefits of MIMO and also to provide high beamforming gain to overcome the high propagation loss in mmwave bands for 5 G cellular communications (Ahmed et al., 2018).

Considered the single-user mmwave MIMO system as described in (Fig. 2) in Ref (Li and Masouros, 2017), (3) in (Le and Zhao, 2020) in which the base station is connected with N_t transmission antenna and R_F chain communicates N_S data stream to N_r receiving antennas, satisfying the condition $Ns \leq NRF£Nt$; In the transmitter side, first data streams N_s are transmitted to $N_{RF}R_F$ chains by an $N_{RF}\acute{N}_S$ digital precoding matrix F_{BB}, then an $N_t \times N_{RF}$ analog precoding matrix F_{RF} as usual transmit these data streams to N_t transmitting antennas (Kasai, 2018).

In a fully connected hybrid beamforming structure, each RF chain is connected with all antennas, and the transmitted signal on each of the *NRF* digital transceivers goes through *NtRF* paths (mixer, power amplifier, phase shifter, etc.) and summed up before being connected with each antenna, see Fig. 3. The fully connected structure can make full use of the degrees of freedom (DOF) of precoding provided by the RF chains.

Accordingly, the transmitted signal can be expressed (Raisa et al., 2019) as follows:

$$x = F_{RF}F_{BB}S \tag{1}$$

where S is the symbol vector $(N_s \times 1)$

$F_{RF} = N_{TX}\acute{}N_{RF}$ is the analog precoding matrix

$F_{BB} = N_{RF}\acute{}N_S$ is the digital precoding matrix

The received signal y at the user is given by (Kaushik et al., 2016)

$$y = \sqrt{\rho}\, H\, F_{RF}\, F_{BB}\, s + n \tag{2}$$

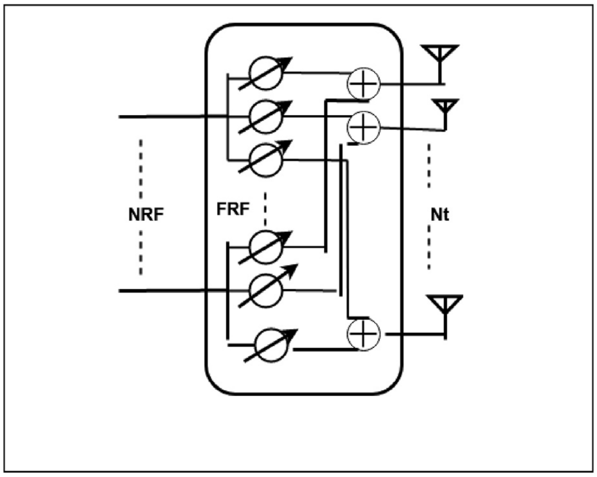

Fig. 3. Transmitter array structure with a fully connected structure.

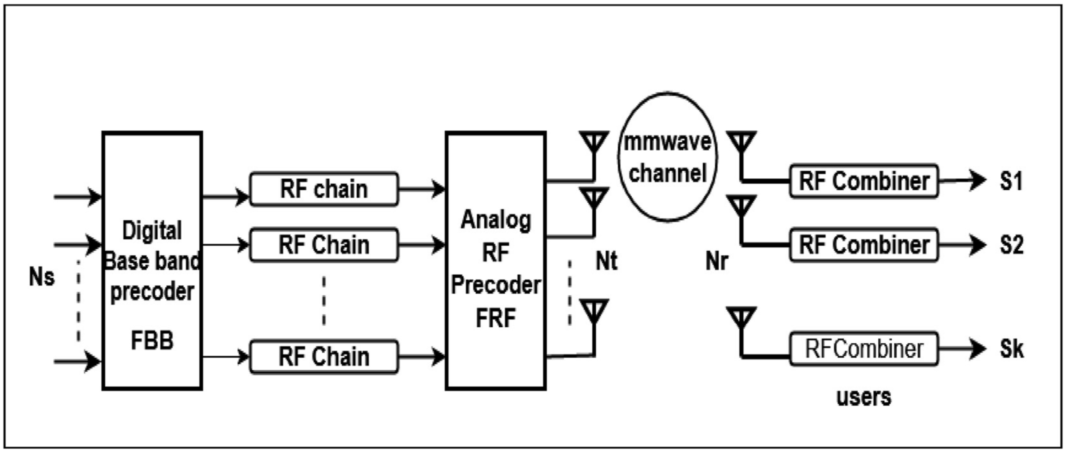

Fig. 2. Block diagram of the system model.

Table 1. Parameter definition.

Parameter	Definition
S	Symbol vector
F_{RF}	Analog precoding matrix
F_{BB}	Digital precoding matrix
ρ	Average received power
H	Channel matrix
n	Additive white Gaussian noise (AWGN)
γ	Normalization factor
Ncl	Scattering cluster
$Nray$	Propagation paths in each cluster
a_{il}	Complex gain of the *lth* ray in the *ith* scattering cluster
f_{il}^{r} (f_{il}^{t})	Azimuth angles of arrival (AoAs)
θ_{il}^{r} (θ_{il}^{t})	Elevation angles of departure (AoDs)
$\Lambda_t(f_{il}^{t}, \theta_{il}^{t})$, $\Lambda_r(f_{il}^{r}, \theta_{il}^{r})$	Transmit antenna element gain at the corresponding angles of departure and arrival
$a_t(f_{il}^{t}, \theta_{il}^{t})$	Normalized vectors of transmit array response at an azimuth angle
$a_r(f_{il}^{r}, \theta_{il}^{r})$	Receive array response at an elevation angle

where the average received power is ρ, H is the channel matrix $\epsilon\ C^{N_R \times N_T}$, and n is the additive white Gaussian noise (AWGN) vector with zero mean and variance δ^2 equal to 1.

3. Channel model

Due to the high free-space path loss of the mmwave signal, limited spatial scattering usually occurred. Based on Saleh-Valenzuela channel model, the channel matrix H can be expressed (Ya et al., 2016) as follows (Table 1):

$$\mathrm{H} = \gamma \sum_{i,l} a_{il} \Lambda_r\left(f_{il}^{r}, \theta_{il}^{r}\right) \Lambda_t\left(f_{il}^{t}, \theta_{il}^{t}\right) a_r\left(f_{il}^{r}, \theta_{il}^{r}\right) a_t\left(f_{il}^{t}, \theta_{il}^{t}\right)^{H} \tag{3}$$

$$\gamma = \sqrt{N_t N_r \,/ N_{cl} N_{ray}} \tag{4}$$

When using N- elements uniform linear array (ULA). then the array response vector can be expressed in (Gupta et al., 2020) as (6), where $k = 2\,\pi\,/\,\lambda$ and λ is the wavelength of the signal, d the spacing between inter-elements.

$$a_{ULA}(f, \theta) = \frac{1}{\sqrt{N}}\left[1, e^{JKd\,\sin(f)}, \ldots\ldots, e^{JKd(N-1)\sin(f)}\right]^{T} \tag{5}$$

In addition, uniform planner array (UPA) with W and H elements can be used. The array response vector is given by (El Ayach et al., 2014) as (7), where: $0£m£W$, $0£n£H$, and the antenna array size is $N = WH$, $k = 2\,\pi\,/\,\lambda$ and λ is the wavelength of the signal and d the spacing between inter-elements:

The received signal for the mmwave MIMO system model after precoding and before combining (for a single user):

$$y_{N_{MS}\times 1} = HX + n = HF_{BB}F_{RF}s + n = HFs + n \tag{7}$$

RF and BB combiners have been applied, the output signal in Ref (Tatineni, 2019) becomes

$$y^{\sim} = W_{BB}^{H} W_{RF}^{H} y = W_{BB}^{H} W_{RF}^{H} Hx + W_{BB}^{H} W_{RF}^{H} n \tag{8}$$

$$y^{\sim} = W_{BB}^{H} W_{RF}^{H} HF_{BB}F_{RF}s + W_{BB}^{H} W_{RF}^{H} n = WHFs + Wn \tag{9}$$

where combiner W is obtained as follows:

$$W = W_{BB}^{H} W_{RF}^{H},\, W_{BB}^{H} = N_S \times N_{RF},\, W_{RF}^{H} = N_{RF} \times N_{MS} \tag{10}$$

where the spectral efficiency refers to the ability of a given channel encoding method to utilize bandwidth efficiently. It is defined as the average number of bits per unit of time (bit rate) that can be transmitted per unit of bandwidth (bits per second per Hertz) (Tomazic, 2008). Therefore, the spectral efficiency R is expressed as follows (Le and Zhao, 2020):

$$R = \log_2\left(\left| I_{NS} + \frac{\rho}{\sigma^2 N_s} H\, F_{RF} F_{BB} F_{BB}^{H} F_{RF}^{H}\, H^{H} \right|\right) \tag{11}$$

The main objective for using the optimal hybrid precoding is to increase the spectral efficiency of mmWave MIMO systems, and the problem can be formulated as

$$\left(F_{BB}^{OUT}, F_{RF}^{OUT}\right) = \arg\max R \tag{12}$$

$$\left|[F_{RF}]_{i,j}\right| = \frac{1}{\sqrt{N_t}} \tag{13}$$

$$\|F_{BB}F_{RF}\|_F^2 = N_S \tag{14}$$

This problem can be solved using the orthogonal matching pursuit (OMP) algorithm, where the OMP is an algorithm to recover a high-dimensional sparse signal based on a small number of noisy linear measurements. In this algorithm, the AOA/AOD space is divided into grids. Then create a dictionary corresponding to the array response vectors of all the possible angles of arrivals/departures. The dictionary size depends on individual

$$a_{UpA}(f, \theta) = \frac{1}{\sqrt{N}}\left[1, ., e^{JKd\left(\mathrm{m}\ \sin(f)\cos(\theta) + n\ \cos(\theta)\right)}, \ldots\ldots, e^{JKd\left((W-1)\sin(f)\sin(\theta) + (H-1)\cos(\theta)\right)}\right]^{T} \tag{6}$$

resolution where all the received array response vectors corresponding to a specific resolution may be placed (Tatineni, 2019).

In an mmwave system, the multipath dominant components are very few, the problem is solved on a path-by-path basis, which is an efficient way of doing estimation for better accuracy.

4. Simulation results

In this section, the results have been simulated by MATLAB to describe and analyze the mmwave MIMO system of MMSE hybrid precoding/combining, considering the MIMO system model in the last section, the BS is employing with $N_t = 16, 64$ transmit antennas and the $N_r = 16, 64$ receive antennas. The channels are single-path and multipath, the azimuth AoAs/AoDs are assumed to be uniformly distributed in [0; 2π] and the elevation AoAs/AoDs are uniformly distributed in [-π/2, π/2]; all parameters are shown in Table 2.

First, the performance of MMSE hybrid analog/digital precoding algorithm is studied and then compared the results with zero forcing precoder and analog-only beamforming at single paths and multipaths.

From (Fig. 4a and b and Table 3), it can be observed the numerical results in spectral efficiency Vs SNR for MMSE, ZF, and analog-only beam steering. The MMSE hybrid precoding scheme presented results close to zero forcing and achieves better spectral efficiency than the analog-only beamforming.

It can be observed the results of Ref (Le and Zhao, 2020) at only single path channel with SNR = 10 (dB), the spectral efficiency for analog-only beamforming equal to 5.6929 and the spectral efficiency for zero forcing is 10.07, but for MMSE equal to 10.1. however, at multipath channel (L = 10) the spectral efficiency decreased to 6.74 for MMSE, 6.4 for ZF, and 2.985 for analog-only beam steering.

According to the above results, it has been observed that the number of paths affects the spectral efficiency. Fig. 5 shows the results of MMSE hybrid precoding in different paths (L = 5, 10, 20, 30) to study this effect.

From Fig. 5, Tables 4 and 5 it can be noted that the spectral efficiency for L = 5 and L = 10 is 7.729 and

Table 2. Simulation parameter.

Simulation parameter	
N_{TX}	16,64
N_{RX}	16,64
RF chains	4, 6
Ncl	8
Nray	10
Ns	1
SNR dB	−20:5:10

Table 3. Spectral Efficiency results vs. SNR.

SNR = 10(dB)	Spectral Efficiency (bps/Hz)		
	MMSE	ZF	Analog-only beam steering
L = 1 as ref (Le and Zhao, 2020)	10.1	10.07	5.7
L = 10	6.74	6.4	2.985

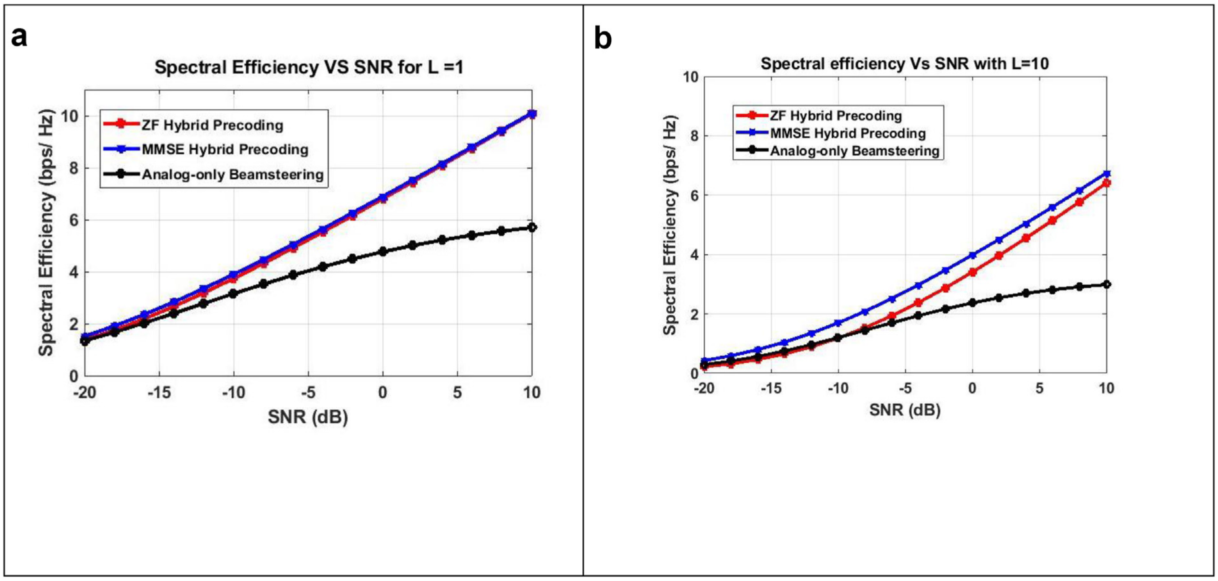

Fig. 4. a: Spectral efficiency vs SNR for single path (L = 1). b: Spectral efficiency vs SNR for single path (L = 10).

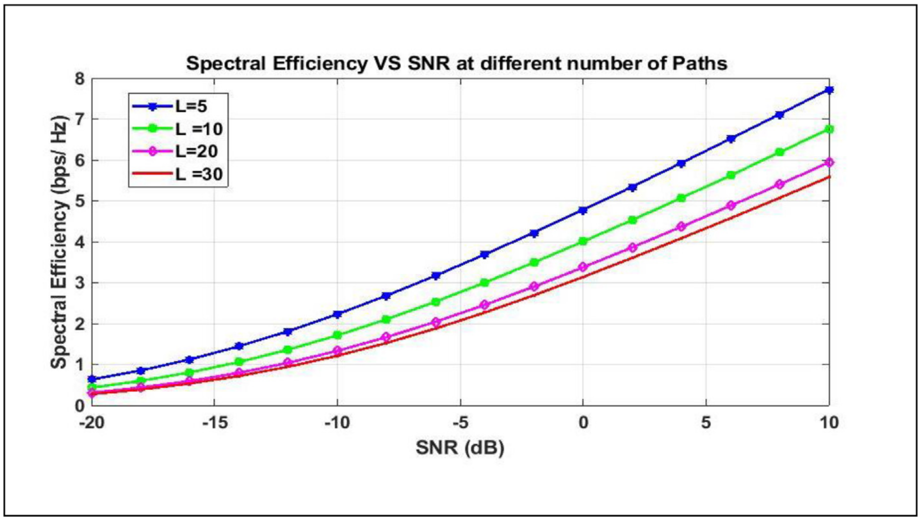

Fig. 5. Spectral efficiency for MMSE hybrid precoding vs SNR with different numbers of paths L = 5, 10, 20, and 30.

Table 4. Spectral efficiency values VS SNR for L = 5,10,20, and 30.

SNR	Spectral Efficiency (bps/Hz)			
	L = 5	L = 10	L = 20	L = 30
SNR = 10 (dB)	7.73	6.7595	5.9363	5.5797

Table 5. Percentage decrease in Spectral Efficiency for L = 30 over L = 5,10, and 20.

SNR	Percentage decrease in spectral efficiency for L = 30 over		
	L = 5	L = 10	L = 20
SNR = 10 (dB)	28%	17.5%	6%

6.7595, respectively, while at L = 20 and L = 30, the spectral efficiency is 5.9363, and 5.5797, respectively. It means that when using multipaths the rate of spectral efficiency is decreasing with 28% in L = 5, 17% in L = 10, 6% in L = 20. According to the previous results, in order to reduce the effect of paths number, the number of antennas shall be increased as shown in Fig. 6.

Fig. 5 and Table 6 show that the spectral efficiency of MMSE at $N_t = 50$ is 60.1223 but when using ZF at the same N_t the spectral efficiency is 41.55, but with analog-only beamforming is 24.08, while at high $N_t = 100$ the spectral efficiency reaches 90.43 in

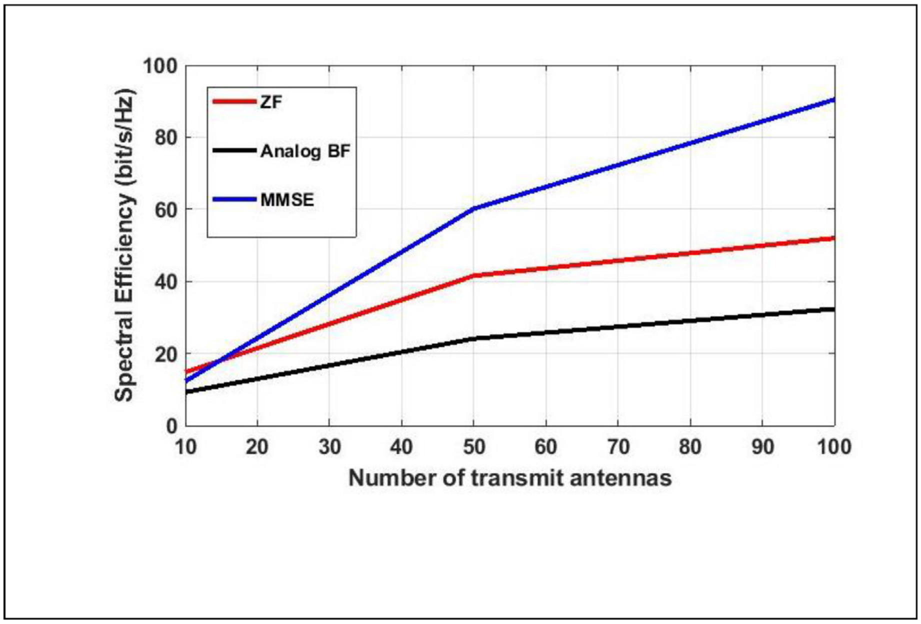

Fig. 6. Spectral efficiency varying the number of transmit antenna in multipath scenario (L = 10).

Table 6. Spectral efficiency values VS different numbers of transmit antenna for MMSE, ZF, analog-only beamforming mmwave MIMO.

Number of transmit antennas	Spectral efficiency for mmwave MIMO		
	MMSE	ZF	Analog-only beamforming
Nt = 50	60.1223	41.55	24.08
Nt = 100	90.43	51.9	32.34

MMSE case, and arrive to 51.9 at the ZF case, and becomes 32.34 at analog-only beamforming.

According to the previous results, the MMSE precoding performs better spectral efficiency than the analog beamform and is very close to ZF. However, with a large number of antennas, the MMSE gives high significance than other hybrid precoding approaches. So, can one can study the MMSE hybrid precoding/combining at the single path and multipaths and compare the results with a single user and analog-only precoding.

The proposed approach is hybrid precoding in the transmitter side and combining in the receiver side using the MMSE approach to maximize the spectral efficiency and study the results in different cases such as different RF chains, different numbers of antennas in BS and MS, and different number of paths.

4.1. Single path channel L = 1

In this section, the results have been simulated using MATLAB to describe and analyze the efficiency of the wireless MIMO system over mmWave frequencies. Also, a comparison is made between the simulation results for the implemented MIMO wireless system using hybrid precoding/combining with a single user and analog-only beamforming at the single path.

In addition, the effect of the RF chain was studied on the system efficiency with (16 × 16 MIMO System), (64 × 16 MIMO System), and (64 × 64 MIMO System).

All the above-mentioned trials were applied to obtain the most improved performance for the system.

From Fig. 7a, b and Table 7 it can be noticed that the spectral efficiency at SNR = 10 dB reaches 7.167 when using 4 RF, but by using 6 RF at the same SNR the spectral efficiency equals 5.6828. However, in analog-only beamsteering case, the spectral efficiency arrives at 2.934 and 1.9989 at 4RF and 6RF at the same SNR, respectively. It means the performance of analog-only beamsteering and hybrid precoding are decreasing with increased RF quantization bits.

It can be considered that the results in Ref (El Ayach et al., 2014) for (8 × 8) the spectral efficiency for hybrid precoding is 6.8 (bps/Hz) and for analog-

Table 7. Spectral efficiency for 16 × 16 at different RF chains with L = 1.

NRF = 4	Spectral efficiency (bps/Hz)		
	Single user	Hybrid precoding	Analog-only beam steering
SNR = −20 dB	0.63726	0.4009	0.51774
SNR = 10 dB	8.555	7.167	2.934
NRF = 6	Single user	Hybrid precoding	Analog-only beam steering
SNR = −20 dB	0.455	0.20355	0.35215
SNR = 10 dB	7.9188	5.6828	1.9989

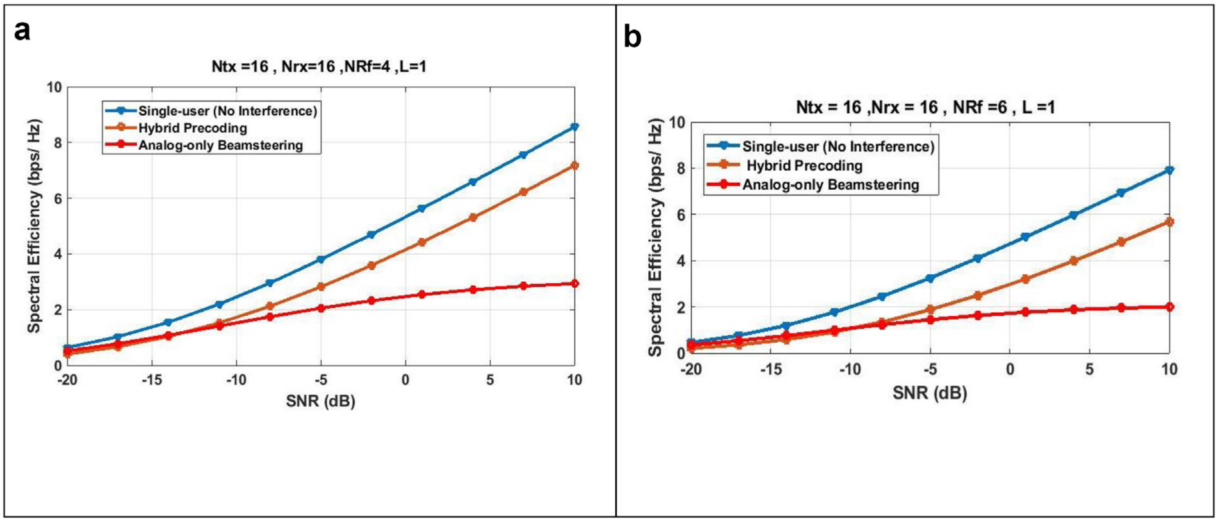

Fig. 7. (a) Spectral efficiency VS SNR for 16 × 16 with 4 RF chains and (b) spectral efficiency VS SNR for 16 × 16 with 6 RF chains.

Table 8. Comparison between results in Ref (El Ayach et al., 2014) and our results.

	Single user	Hybrid precoding	Analog-only beamsteering
Ref (El Ayach et al., 2014) (8 × 8) MIMO SNR = 10 dB		6.8	2.8
Our result for (16 × 16) MIMO SNR = 10 dB	8.555	7.167	2.934

only beamforming is 2.8 (bps/Hz).so can be observed the relation between the spectral efficiency and number of antennas (Table 8).

Fig. 8 describes the relation between spectral efficiency and SNR when increasing the number of antennas in BS to be 64 × 16 MIMO System.

Fig. 8a, b and Table 9 present (64 × 16) MIMO system and single path with different RFs. It can explain the spectral efficiency values when using different number antennas of BS and MS and also the varying RF. For the hybrid precoding case with 16 × 16, at SNR = 10 dB the spectral efficiency is equal to 7.167 and 5.6828 with 4 RF and 6 RF, respectively, at the same SNR. But, for the hybrid precoding case with 64 × 16, at SNR = 10 dB the spectral efficiency is equal to 10.0357 and 9.037 with 4 RF and 6 RF, respectively. That means when using a large number of BS antennas, the spectral efficiency is improved.

4.2. Multipath channel $L = 10$

In this section, it can be studied the MMSE hybrid precoding/combining at the multipath channel for the (16 × 16) MIMO system, (64 × 16) MIMO system, and the (64 × 64) MIMO system.

Fig. 9a, b and Table 10 describe and explain the (16 × 16) MIMO system with multi-path channel L = 10 with different RFs.

Where the spectral efficiency value for analog-only beamsteering is found to be 1.4596 and 2.84 with 4 RF and 6 RF, respectively, but the spectral efficiency value at the SNR = 10 dB equal to 3.9669 and 2.84 with 4 RF and 6 RF, respectively, for the hybrid precoding technique. It means that when using multipath the rate of spectral efficiency is decreasing, and using a large number of RF quantization bits with a large number of BS antennas to avoid the decrease in performance.

Fig. 10 The relation between spectral efficiency and SNR for the 64 × 16 MIMO system.

Fig. 10a, b and Table 10 presents the (64 × 16) MIMO System and multipath L = 10 with different RFs. The spectral efficiency result for analog-only beam steering at SNR = 10 dB is equal to 2.952, and 2.1531 with 4RF and 6RF, respectively, while,

Table 9. Spectral efficiency for 64 × 16 at different RF chains with L = 1.

NRF = 4	Spectral efficiency (bps/Hz)		
	Single user	Hybrid precoding	Analog-only beamsteering
SNR = −20 dB	1.5235	1.3396	1.3396
SNR = 10 dB	10.4923	10.0357	5.7827
NRF = 6	Single user	Hybrid precoding	Analog-only beamsteering
SNR = −20 dB	1.1807	0.97837	0.97837
SNR = 10 dB	9.824	9.0327	4.2854

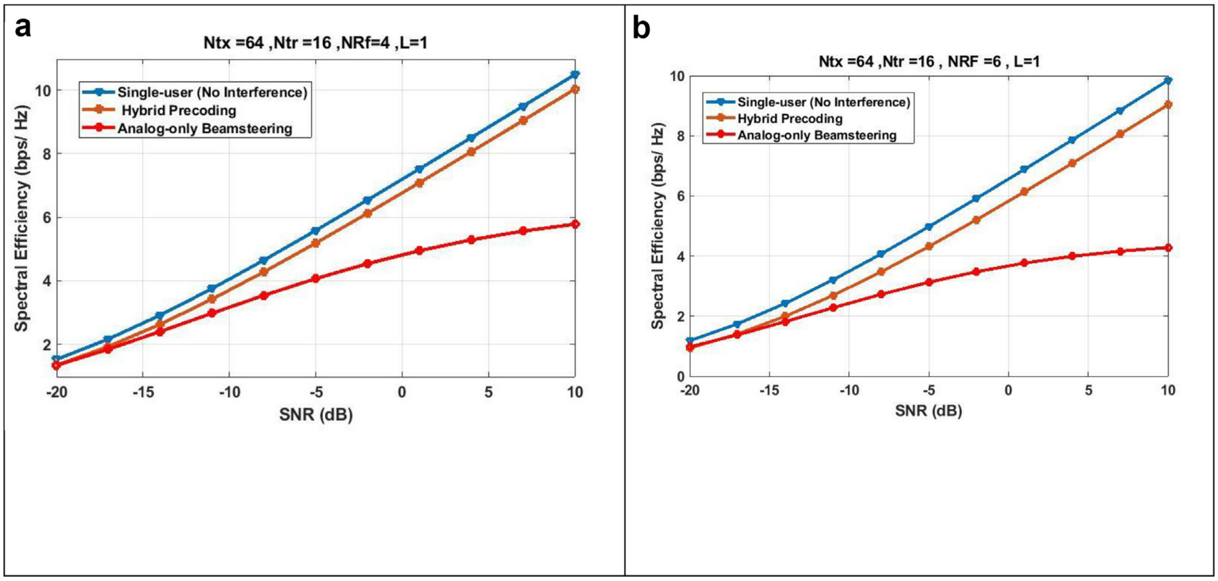

Fig. 8. a: Spectral efficiency VS SNR for 64 × 16 with 4 RF chains. (b): Spectral efficiency versus SNR for 64 × 16 with 6 RF chains.

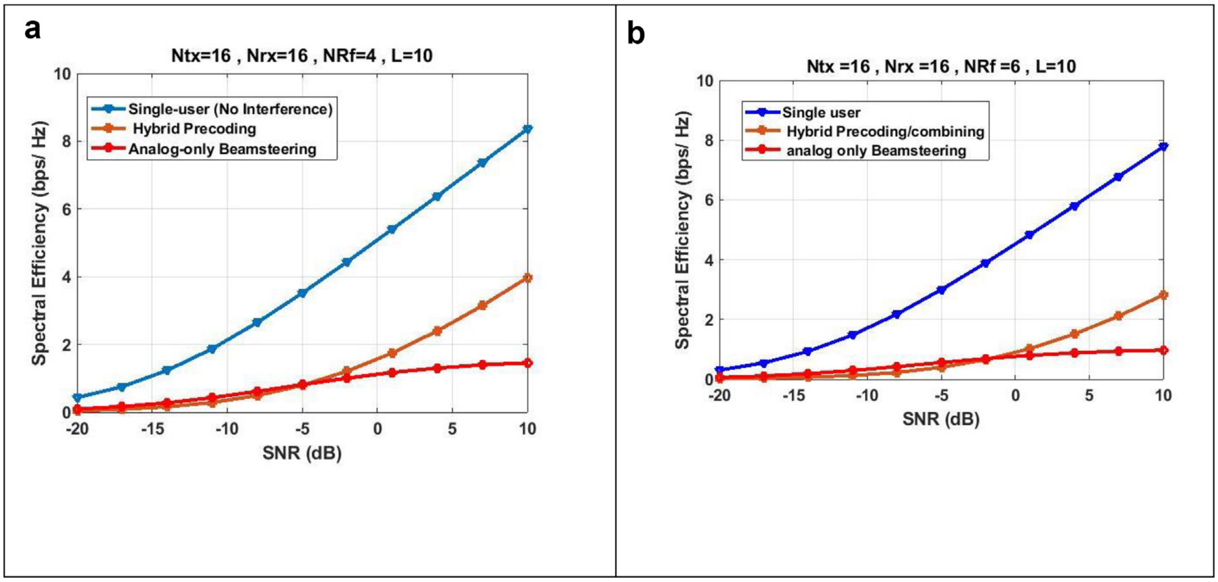

Fig. 9. (a) Spectral efficiency VS SNR for 16 × 16 with 4 RF chains. (b) spectral efficiency VS SNR for 16 × 16 with 6 RF chains.

Table 10. Spectral efficiency for 16 × 16 at different RF chains with L = 10.

Spectral efficiency (bps/Hz)			
NRF = 4	Single user	Hybrid precoding	Analog-only beamsteering
SNR = −20 dB	0.43	0.092	0.092
SNR = 10 dB	8.357	3.9669	1.4596
NRF = 6	Single user	Hybrid precoding	Analog-only beamsteering
SNR = −20 dB	0.3042	0.0639	0.00639
SNR = 10 dB	7.78	2.84	1.009

spectral efficiency for hybrid precoding at SNR = 10 with 4RF dB is equal to 6.4419 and with 6RF it is equal to 5.3236, this means that the spectral efficiency of the hybrid precoding technique and analog-only beam steering decreases with increased RF chain and using a large number of BS antennas makes the system improved.

Fig. 11 studies the effect of increasing the number of antennas in MS and Table 11 presents the improvement values with different numbers of antennas in both BS and MS.

From (Tables 12 and 13) it can be observed that the improvement in spectral efficiency VS SNR with an increase in the number of antennas in both BS and MS, where the spectral efficiency value is 3.9669 in the hybrid precoding technique at the (16 × 16) MIMO system but in (64 × 16) MIMO the spectral efficiency reaches 6.4419 at the same SNR value,

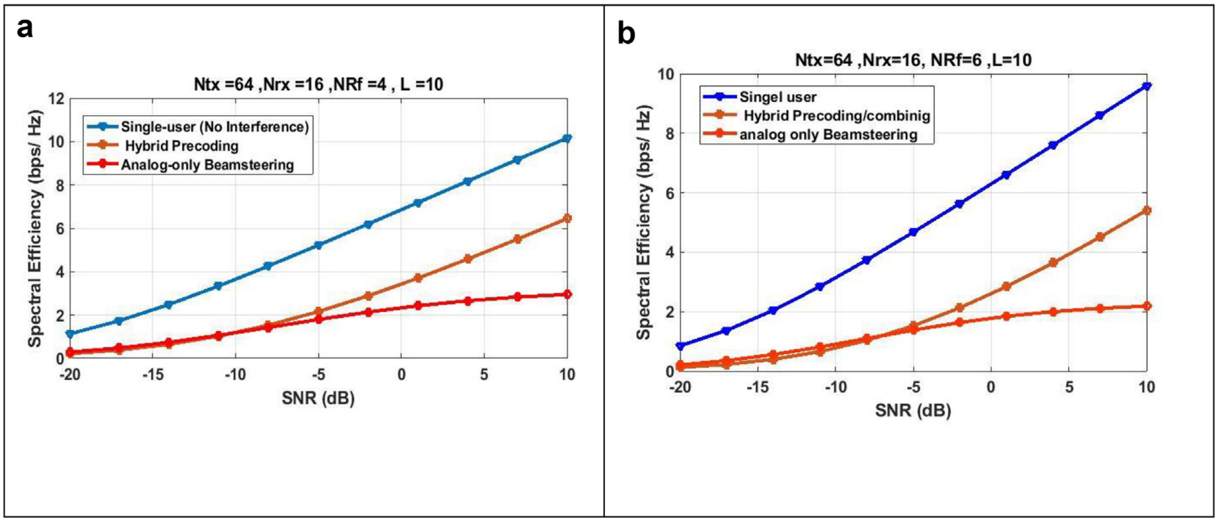

Fig. 10. (a) Spectral efficiency VS SNR for 64 × 16 with 4 RF chains. (b) Spectral efficiency VS SNR for 64 × 16 with 6 RF chains.

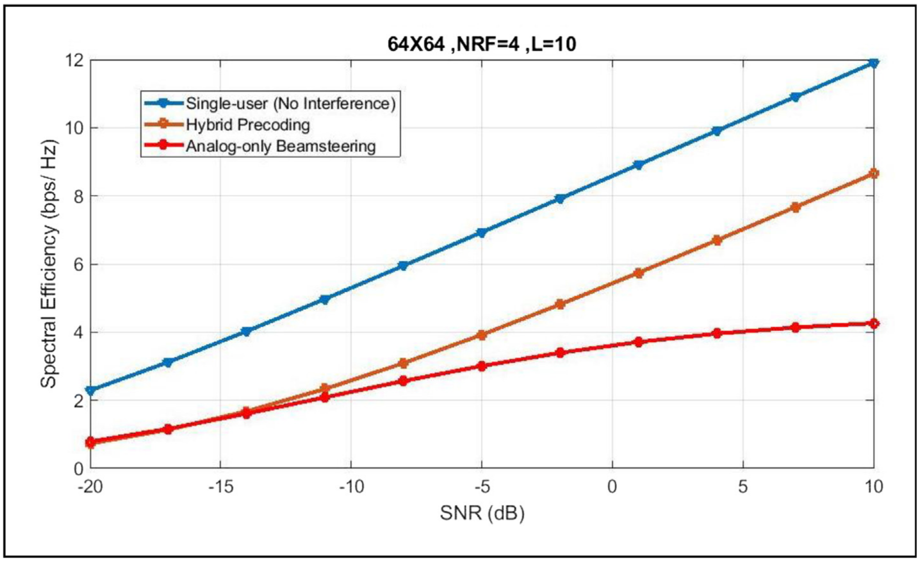

Fig. 11. Spectral Efficiency VS SNR for 64 × 64 with 4 RF chains.

Table 11. Spectral efficiency for 64 × 16 at different RF chains with L = 10.

Spectral efficiency (bps/Hz)			
NRF = 4	Single user	Hybrid precoding	Analog-only beamsteering
SNR = −20 dB	1.129	0.2896	0.2896
SNR = 10 dB	10.1626	6.4419	2.952
NRF = 6	Single user	Hybrid precoding	Analog-only beam steering
SNR = −20 dB	0.853	0.20587	0.20587
SNR = 10 dB	9.59	5.3236	2.1531

which means a percentage improvement of up to 38% than (16 × 16) MIMO. However, when increasing the number of antennas in MS to be (64 × 64) MIMO the spectral efficiency becomes 8.445 with a percentage improvement reaching 24% than (64 × 16) MIMO, which means the spectral efficiency improved with increasing the number of antennas in both BS and MS.

Table 12. Spectral efficiency Vs SNR for different numbers of antennas.

SNR	Spectral efficiency for 16 × 16 at 4 RF chain		
	Single user	Hybrid precoding	Analog-only Beam steering
SNR = 10 dB	8.357	3.9669	1.4596
SNR	Spectral efficiency for 64 × 16 at 4 RF chains		
	Single user	Hybrid precoding	Analog-only beamsteering
SNR = 10 dB	10.1626	6.4419	2.952
SNR	Spectral efficiency for 64 × 64 at 4 RF chains		
	Single user	Hybrid precoding	Analog-only beamsteering
SNR = 10 dB	11.89	8.445	4

Table 13. Percentage improvement in spectral efficiency for hybrid precoding

SNR	Percentage improvement in spectral efficiency for Hybrid precoding at 4 RF chains of (64 × 64) MIMO over	
	16 × 16 MIMO	64 × 16 MIMO
SNR = 10 dB	53%	24%

4.3. Conclusion

This paper gives a comparison analysis and improvement for hybrid precoding at the transmitter and combining in receiver mmwave MIMO system with analog-beamsteering and digital precoding for single/multiuser and single/multipath channel based on the OMP algorithm. In addition, the MMSE precoder is studied and compared with analog-only beamforming and ZF.

The MATLAB simulation results give the MMSE hybrid precoding scheme that presented results close to zero forcing and achieves better spectral efficiency than analog-only beamforming. However, multipath channels reduce the spectral efficiency values by 27.8%, but using large numbers of antennas the spectral efficiency is improved by approximately 59%. In addition, when studying the relation between RF chains and the behavior of hybrid precoding, it found that the spectral efficiency is decreasing with increased RF quantization bits by 20% for (16 × 16) and by 10% for (64 × 16), so using an increased number of RF chains must increase the number of antennas to avoid the decreasing the overall performance of systems.

Suggested future direction related to such mmWave precoding includes evaluating other types of performance parameters. Also, research in the hybrid precoding for mmWave massive MIMO systems in 6G is recommended.

Author contribution

Youstina N. Samir: Data curation, writing, original draft preparation. **Hala B. Nafea**: conceptualization, methodology, editing the Manuscript; **Fayez W. Zaki**: visualization, investigation, and review.

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