

Massive MIMO Systems Precoder Design Under Various Environments



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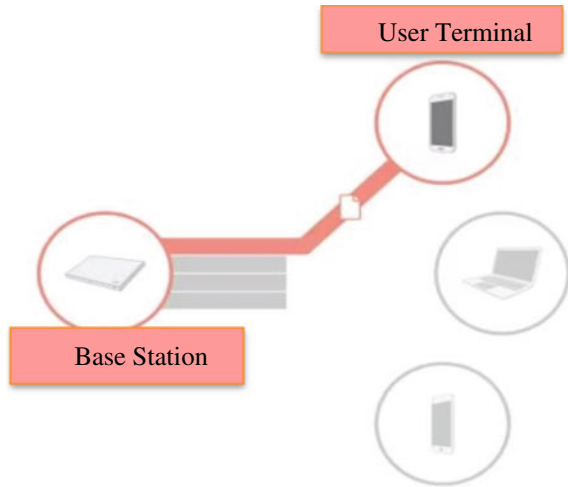
1 Introduction

In the current wireless scenario where the number of users and achievable rate has considerably increased and it incorporates multi-user MIMO system [1]. The MIMO technology enables multiple transmission of signals to large number of user terminals by employing multiple antenna elements at the transmitter. The organization of such multiple signals from multiple user terminals is coined as beamforming. The generalization of beamforming is also known as precoding. Fading is an important parameter in any wireless system that should be reduced significantly. MIMO technology plays a vital role in minimizing the fading effects in wireless channels by allowing multiple transmissions of the same signal by employing large number of antenna arrays at the base station. At the mobile receiver terminal (MRT), the losses incurred due to fading is significantly reduced by multiple transmission of the same signal and the rate at which the signals are combined given by maximum ratio combining (MRC). If the channels between the transmitter and receiver are assumed to be virtual in a MIMO system, then the throughput of the system can be maximized. Figure 1 illustrates the single-user MIMO (SU-MIMO) where only a single user can be provided with the access at a particular time and termed as conventional MIMO scheme. Since the single-user MIMO had several drawbacks and did not address many of practical applications so the researchers moved to a change in MIMO system.

Figure 2 illustrates the multi-user MIMO along with the space division multiple access (SDMA) [2]. A multi-user MIMO system can serve more than two user terminals but the major drawback is computational complexity. In addition, in such wireless systems that employ multiple user MIMO the drawback is the interface

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Fig. 1 Single-user MIMO

between the user terminals. As the number of user terminals increases, the interface maintenance between the terminals is difficult since they are controlled by a single base station. This limitation is resolved by employing signal processing techniques at the transmitting side of a MIMO system. So, if the channel state information (CSIT) is known at the transmitter, then the gain and throughput of the system can be significantly improved compared to conventional schemes.

Wireless communication technology in recent days has gained significant attention as it could incorporate hundreds to thousands of antennas at the base station as shown in Fig. 3. The concept of massive MIMO system is typically used for 5G and 6G applications by providing coverage to smaller L number of users per cell by means of a base station along with acceptable N number of antennas, $N \ll L$ [3]. The coverage provided by a massive MIMO system is significantly very high when compared with multi-user MIMO. Various signal processing techniques are performed at the transmitter in order to improve the number of users and gain of the system to enhance the throughput.

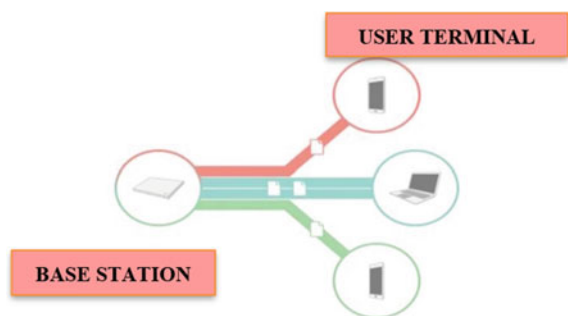
Fig. 2 Multi-user MIMO

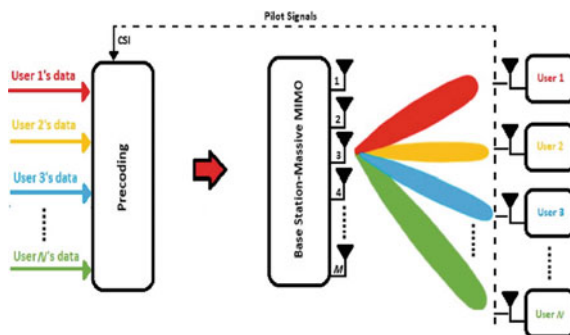
Fig. 3 Massive MIMO

The preprocessing stage of the RF system employs a transmit signal processing technique such as precoding. The spectral efficiency of a MIMO system can be improved significantly by knowing the channel state information (CSI) at the transmitter and by performing precoding techniques at the base station. In conventional techniques, the complexity of the system is addressed at the receiver side which is transformed to the base station by performing signal processing techniques at the transmitter side such as precoding in a massive MIMO system. The next promising issue in most real-time scenarios is to maintain a perfect CSI at the transmitter for different wireless propagation channels. Many researchers have found that MIMO precoding techniques significantly improve the system performance and throughput by varying the beam angles and leading them to a specific user terminal. The precoding techniques of a massive MIMO system involve infinite antennas that enhance the throughput and capacity of the system by reducing the properties of fading and interference. The precoding is broadly divided into several categories such as linear and nonlinear techniques. Precoding along with beamforming is used together in Wi-Fi, 4G, and 5G systems. Multi-user interference (MUI) can be mitigated by using simple precoding algorithm called as zero forcing (ZF) [4]. This paper proposes different precoding techniques for wireless communication channels under various environments for a massive MIMO-based OFDM system. The simulation results are then compared with other precoding techniques in terms of bit error rate (BER) and signal-to-noise ratio (SNR). Then the best precoding algorithm is identified and employed for various applications.

2 Linear Precoding Algorithms

Linear precoding is also known as beamforming, and it is a particular subclass of schemes transmission that serves multiple users at the time. The given weights of user are selected in precoding to maximize the ratio between the signal gain at this user and the interference generated at other users (with some weights of users) plus noise. Linear precoding is more attractive for large-scale MIMO. In multi-user

Fig. 4 Massive MIMO with linear precoding

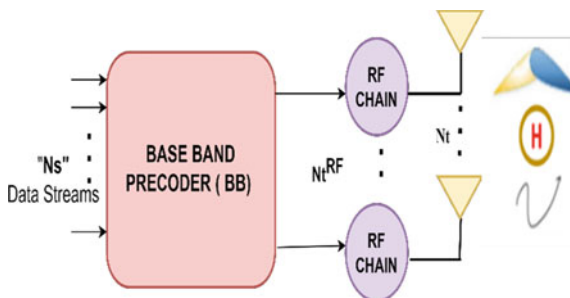


MIMO system, it provides high capacity with space division multiple access [19]. The channel state information if available at base station (BS) or access point (AP), then multi-user information can be suppressed. Precoding allows to perform many complex processing at base station or AP. It helps simplification at users end, the linear precoding techniques. But nonlinear techniques yield better performance (Fig. 4).

For obtaining accurate gain and phase the multi-user MIMO and massive MIMO incorporates precoding schemes (hybrid beamforming). The N_s data streams are passed into the base band precoder and the weights are computed to be passed into number of RF chains and then to the analog precoder as shown in Fig. 5 to compute the channel matrix $[H]$.

In massive MIMO systems, the technique of precoding enables multiple versions of data from different user terminals by assigning weights to every signal that originates from every antenna element separately. The main principle of the precoder is to determine the precoding weight vector in such a way that it improves the link throughput of the system at the receiver terminal. The authors of [5] Keke Zu have presented many linear precoding techniques in a detailed manner. He concluded by the fact that the computational complexity of the MIMO system is directly proportional to the number of antenna array elements at the base station. Thus, there is always a trade-off between the complexity and efficiency of the massive MIMO system.

Fig. 5 Digital precoding



2.1 Minimum Mean Square Error (MMSE) Algorithm

The MMSE algorithm is based on the computation of mean square error and finding the minimum among them for a MIMO system. Bahrami et al. [6] illustrated that the linear precoding techniques such as maximum ratio transmission (MRT), zero forcing (ZF), and MMSE are low complexity algorithms and simple but with the drawback is poor performance. In conventional systems, the reversal property of the channel is used but MMSE-based precoding technique employs regularized version of channel inversion as function of balancing the magnitude of the signal along with its alignment and noise compression termed as tuning in MMSE expression. Specifically tuning a function in MMSE is to vary the parameters in a regularized manner. For practical applications, MMSE-based precoding mainly concentrates on the antenna array structure and the number of antenna elements used. For a MMSE-based MIMO system, the precoding matrix is,

$$P_{\text{MMSE}} = \frac{1}{\beta} H^H \left(H H^H + \frac{N_u}{P_{\text{tr}}} I_{N_u} \right)^{-1} \quad (1)$$

Then, the vector at the receiver terminal of a MMSE-based precoder is,

$$y = \frac{1}{\beta} H \left[H^H \left(H H^H + \frac{N_u}{P_{\text{tr}}} I_{N_u} \right)^{-1} \right] x + n. \quad (2)$$

where

$$\beta = \sqrt{\frac{\text{tr} \left(H^H \left(H H^H + \frac{N_u}{P_{\text{tr}}} I_{N_u} \right)^{-1} \right)}{P_{\text{tr}}}}. \quad (3)$$

From the above expressions, it is evident that MMSE-based precoders usually offer a trade-off between the maximum ratio transmission (MRT) and zero forcing (ZF) algorithm [12] and it also proves that the performance of the system has significantly improved even if the wireless channel is noisy when compared with zero forcing (ZF) technique [13]. The major advantage of MMSE is that it eliminates the inter-user interference (IUI) and offers an optimal achievable rate even in the presence of noise [14] for all types of propagation channels.

2.2 Maximum Ratio Transmission Algorithm

Maximum ratio transmission algorithm performs beamforming at the transmitter side of a MIMO system by employing several antennas at the transmitter and receiver

side for successful transmission of data streams. It allows the system to make use of the same receiver by improving the diversity order [19]. The MRT algorithm is considered for special types of scenario such as two receive antennas and infinite number of transmit antennas for which the probability of error is computed and found to be less compared to other conventional algorithms.

For a MRT-based MIMO system, the precoding matrix is,

$$P_{\text{MRT}} = \frac{1}{\beta} H^H \quad (4)$$

$$\beta = \sqrt{\frac{\text{tr}(\mathbf{B}\mathbf{B}^H)}{P_{\text{tr}}}} \quad (5)$$

Also,

$$B = H^H \quad (6)$$

Then, the vector at the receiver terminal of a MRT-based precoder is,

$$y = \frac{1}{\beta} \mathbf{H}\mathbf{H}^H x + n \quad (7)$$

$$\beta = \sqrt{\frac{\text{tr}(\mathbf{H}\mathbf{H}^H)}{P_{\text{tr}}}} \quad (8)$$

A MIMO system consists of several transmitting schemes that were discussed in many precoding literatures. Wittenben proposed a transmitting algorithm that employs a delayed version of the signal [7, 8]. Also, Seshadri and Winters [9, 10] proposed a similar algorithm by slightly varying the delayed signal by transmitting the repeated versions of the signal continuously through multiple antennas at the base station at different time intervals. Additionally, Alamouti [11] presented a transmit diversity scheme that uses a couple of symbols that are to be transmitted by employing two antennas at the base station initially and again transmits the modified version of the pair of symbols that arrive at the diversity based on maximum ratio transmission (MRT). The proposed algorithm is very simple and provides high efficiency compared to conventional algorithms. Though the preliminary objective of such precoding schemes is to maximize the SNR, it also provides sub-optimal values of achievable sum rate.

Authors of [15] proposed signal processing techniques at the base station for every antenna terminal. The MRT is more adaptable, and its efficiency is near to the optimal performance for any system that has limited noise component [16]. But for such systems to operate efficiently the columns of the propagation matrix need to be orthogonal elements.

2.3 Zero Forcing Algorithm

The multi-user interference (MUI) can be nullified in a multi-user MIMO communication system by employing signal processing techniques to the antenna elements at the base station. The zero forcing (ZF) precoders require pseudo-inversion of the channel matrix $[H]$ known at the transmitter. This algorithm is typically employed for nullifying the inter-user interference (IUI) by re-transmitting the same version of every signal to the receiver. For a ZF-based MIMO system, the precoding matrix is,

$$P_{ZF} = \frac{1}{\beta} H^H (HH^H)^{-1}, \quad (9)$$

where

$$\beta = \sqrt{\frac{\text{tr}(BB^H)}{P_{tr}}} \quad (10)$$

Also,

$$B = H^H (HH^H)^{-1}. \quad (11)$$

Then, the vector at the receiver terminal of a ZF-based precoder is,

$$y = \frac{1}{\beta} H \left[H^H (HH^H)^{-1} \right] x + n, \quad (12)$$

where

$$\beta = \sqrt{\frac{\text{tr}(HH^H (HH^H)^{-2})}{P_{tr}}} \quad (13)$$

The data rate of zero forcing (ZF) algorithm is very high when compared with MRT algorithm [17]. This algorithm completely minimizes the IUI, and there is a trade-off between complexity and efficiency of the MIMO system. For interference-controlled system, the ZF algorithm provides optimal results when compared with MRT and MMSE [18].

3 Results and Analysis

The simulation results were obtained under different environments such as urban, sub-urban, and rural areas. The number of transmitting antennas at the base station was kept at $T = 50$, and the number of user terminals was $N = 4$ for all the scenarios.

The simulation was computed for a massive MIMO system with OFDM type of modulation that consists of fifty-two sub-carriers and 64-bit quadrature amplitude modulation (QAM) modulated symbol under various propagation scenarios. All the simulation results were obtained using MATLAB 2020b.

The analysis has been conducted using the linear precoding algorithms such as zero forcing, minimum mean square error, maximum ratio transmission under the urban scenario with number of transmitting base station antennas $T = 50$, number of users being $N = 4$. The MMSE algorithm is observed to be performing well under this scenario with $\text{BER} = 10^{-5}$ and $\text{SNR} = 16 \text{ dB}$ as shown in Fig. 6. The comparative analysis of various linear algorithms such as ZF, MRT, and MMSE is tabulated in Fig. 7. For urban area scenario, the MMSE algorithm is observed to be performing well under this scenario with $\text{BER} = 10^{-5}$ and $\text{SNR} = 21 \text{ dB}$ as shown in Fig. 8.

Further the analysis has been conducted using the linear precoding algorithms such as zero forcing, minimum mean square error, maximum ratio transmission under the sub-urban scenario with number of transmitting base station antennas $T=50$, number of users being $N=4$.

The comparative analysis of various linear algorithms such as ZF, MRT, and MMSE is tabulated in Fig. 9. for sub-urban area scenario.

The analysis has been conducted using the linear precoding algorithms such as zero forcing, minimum mean square error, maximum ratio transmission under the rural scenario with number of transmitting base station antennas $T = 50$, number of users being $N = 4$. The MMSE algorithm is observed to be performing best under this scenario with $\text{BER} = -2511.88$ and $\text{SNR} = 14\text{dB}$ as shown in Fig. 10.

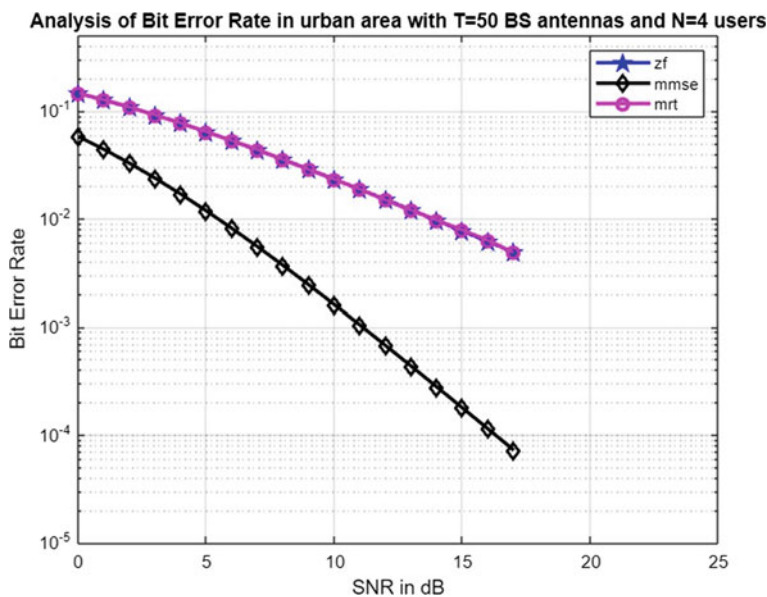


Fig. 6 Urban area scenario

ALGORITHM	NO.OF BASE STATION ANTENNAS	NO.OF USER TERMINALS	BIT ERROR RATE (BER)	SNR (dB)
Zero Forcing (ZF)	50	4	-10^{-2}	17
Maximum Ratio Transmission (MRT)	50	4	-10^{-2}	17
Minimum Mean Square Error (MMSE)	50	4	-10^{-4}	16

Fig. 7 Urban area scenario—comparison of ZF, MRT, and MMSE

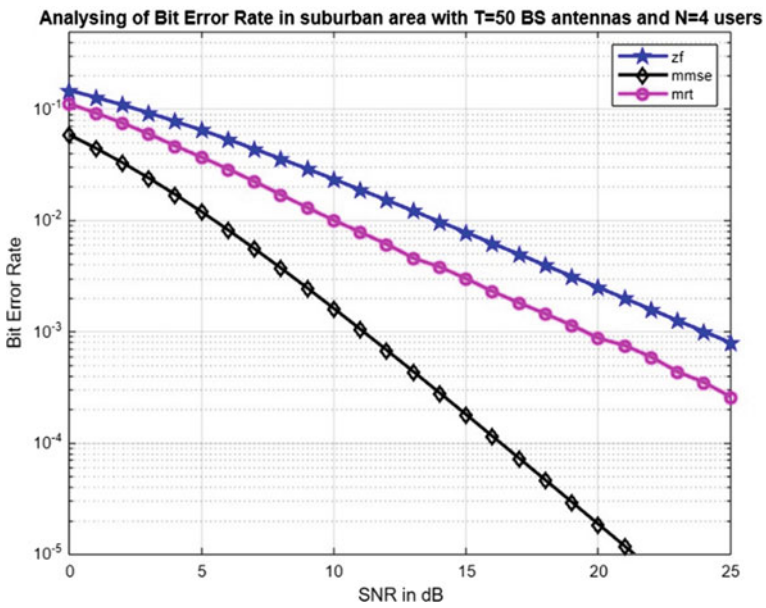


Fig. 8 Sub-urban area scenario

The comparative analysis of various linear algorithms such as ZF, MRT, and MMSE is tabulated in Fig. 11 for rural area scenario.

ALGORITHM	NO.OF BASE STATION ANTENNAS	NO.OF USER TERMINALS	BIT ERROR RATE (BER)	SNR (dB)
Zero Forcing (ZF)	50	4	10^{-3}	25
Maximum Ratio Transmission (MRT)	50	4	10^{-4}	25
Minimum Mean Square Error (MMSE)	50	4	10^{-5}	21

Fig. 9 Sub-urban area scenario—comparison of ZF, MRT, and MMSE

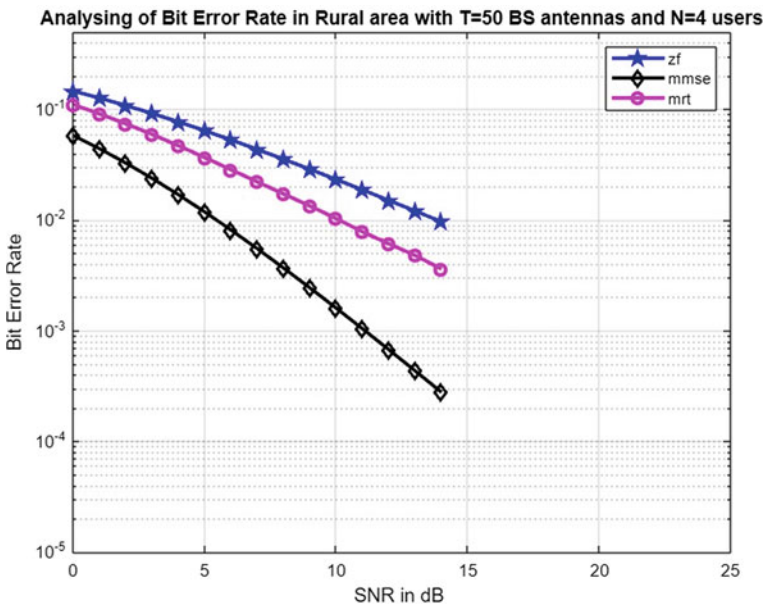


Fig.10 Rural area scenario

ALGORITHM	NO.OF BASE STATION ANTENNAS	NO.OF USER TERMINALS	BIT ERROR RATE (BER)	SNR (dB)
Zero Forcing (ZF)	50	4	-100	15
Maximum Ratio Transmission (MRT)	50	4	-325.5	14
Minimum Mean Square Error (MMSE)	50	4	-2511.88	14

Fig. 11 Rural area scenario—comparison of ZF, MRT, and MMSE

4 Conclusion

This work compares the massive MIMO system incorporated with different linear precoding algorithms such as MRT, MMSE, and ZF under different environments with QAM type of modulation. The bit error rate of all these algorithms under different scenario was tabulated. The matrix inversion is employed to reduce computational complexity of the MMSE-based precoder. The simulation results of MRT under urban scenario proved to be good. To conclude, by comparing different scenarios, it is observed that MMSE has less SNR and less BER among MRT and ZF precoding algorithms. Hence for rural environment, the precoder can be designed using MMSE or RZF algorithm is employed.

5 Future Scope

High-speed Internet and fast access to the network have drastically increased in recent years. The rapid evolution of the mobile technology tremendously increases the number of users and fast services in all the fields. These requirements lead to the Massive MIMO system, and for efficient functioning of such large system, signal processing techniques were incorporated at the base station. Such signal processing techniques were precoding, scheduling, and channel estimation. Linear precoding algorithms, with which we can simulate for a greater number of subscribers. The future work can be extended by employing deep learning algorithms to overcome the computational complexity of these conventional algorithms.

References

1. Qiao X, Zhang Y, Yang L (2018) Conjugate gradient method based linear precoding with low-complexity for massive MIMO systems. In: Proc IEEE 4th International Conference Computer Communication (ICCC), pp 420–424
2. Albreem MA, Juntti M, Shahabuddin S, Massive MIMO detection techniques: a survey. *IEEE Commun Surveys Tuts* 21(4):3109–3132
3. Lee B (2017) ‘Simplified antenna group determination of RS overhead reduced massive MIMO for wireless sensor networks.’ *Sensors* 18(2):84
4. Bahrami H-R, Le-Ngoc T (2008) Maximum ratio combining precoding for multi-antenna relay systems. In: 2008 IEEE International Conference on Communications, pp 820–824. IEEE
5. Emil EGL, Marzetta TL (2016) Massive MIMO: ten myths and one critical question. *IEEE Comm Magazine* 54(2):114–123
6. Bai Y, Liang Z, Zhai C, Xin Y, Li W (2019) Joint precoding using successive over-relaxation matrix inversion and Newton iteration for massive MIMO systems. In: Proc 11th International Conference Wireless Communication Signal Process (WCSP), pp 1–5
7. Seshadri N, Winters J (1993) Two signaling schemes for improving the error performance of FDD transmission systems using transmit antenna diversity. In: Proceedings IEEE Vehicular Technology Conference (VTC), May, pp 508–511
8. Fatema N, Hua G, Xiang Y, Peng D, Natgunanathan I (2018) ‘Massive MIMO linear precoding: a survey.’ *IEEE Syst J* 12(4):3920–3931
9. Albreem MA, Juntti M, Shahabuddin S (2019) Massive MIMO detection techniques: a survey. *IEEE Commun. Surveys Tuts.* 21(4):3109–3132
10. Boccardi F, Huang H (2006) Optimum power allocation for the MIMO-BC zero-forcing precoder with per-antenna power constraints. In: 2006 40th Annual Conference on Information Sciences and Systems, pp 504–504. IEEE
11. Björnson E, Hoydis J, Sanguinetti L (2017) Massive mimo networks: spectral, energy, and hardware efficiency. *Found Trends Sig Process* 11(3–4):154–655
12. Zheng K, Zhao L, Mei J, Shao B, Xiang W, Hanzo L (2015) Survey of large-scale MIMO systems. *IEEE Comm Surveys Tut* 17(3):1738–1760
13. Wittneben A (1991) Base station modulation diversity for digital simulcast. In: Proceedings IEEE Vehicular Technology Conference (VTC), May, pp 848–853
14. Fatema N, Hua G, Xiang Y, Peng D, Natgunanathan I (2018) Massive MIMO linear precoding: a survey. *IEEE Syst J* 12(4):3920–3931
15. Zu K (2013) Novel efficient precoding techniques for multiuser MIMO systems. University of York, PhD diss.
16. Winters J (1994) The diversity gain of transmit diversity in wireless systems in Rayleigh fading. In: Proc ICC/SUPERCOMM, New Orleans, LA, vol 2, pp 1121–1125
17. Chandrasekaran K, Kandasamy P, Ramanathan S (2020) Deep learning and reinforcement learning approach on microgrid. *Int Trans Electr Energ Syst*, e12531. <https://doi.org/10.1002/2050-7038.12531>
18. Alamouti S (1998) A simple transmit diversity technique for wireless communications. *IEEE J Select Areas Commun* 16:1451–1458
19. Subitha D (2020) Analysis of linear precoding techniques for massive MIMO-OFDM systems under various scenarios. In: IOP Conference Series: Materials Science and Engineering, vol 1084. ICCSS