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Design, Simulation & Concept Verification of 4 × 4, 8 × 8 MIMO With ZF, MMSE and BF Detection Schemes

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Abstract **– A conventional MIMO system is designed consisting of 4 antenna elements at both the receiver and transmitter ends. Different kinds of signal detection techniques, namely, zero forcing (ZF), minimum mean square error (MMSE) and beamforming (BF), are used at the receiver end for signal detection. The performance of the system is analyzed by calculating BER vs SNR for each of the above techniques separately. The present work has been thoroughly analyzed and implemented using MATLAB. On the basis of the results obtained, it is summarized that as the values of SNR increase, BER decreases for ZF and MMSE and it almost vanishes to zero even for low SNR values if BF is used. Although ZF and MMSE are suitable for designing a conventional MIMO system with 4 antenna elements, it becomes too difficult for a large number of antenna elements due to its complexity of calculating the inverse of a ($N \times N$) matrix. Based on the results analyzed so far, it is concluded that beamforming (BF) is a suitable technique for designing a system that has a large number of antenna elements at the base station. A further improved system with enhanced performance regarding lower BER for even smaller values of SNR is designed in the present study, consisting of 8 antennas at the base station. The results obtained are enthusiasm-provoking and encouraging for further studies to develop a concept for next-generation wireless communication systems with an optimum design.**

Keywords **– Bit Error Rate (BER); Beamforming (BF); MIMO system; Minimum mean square error (MMSE); Signal to Noise Ratio (SNR); Zero forcing (ZF).**

I. Introduction

MIMO is a multiple-antenna scheme, which uses numerous antennas at both the receiver and transmitter ends to simultaneously transmit multiple signals to a wireless medium and to receive multiple signals from a wireless medium [1]. The MIMO system is an extremely spectrum-efficient technology, which provides higher data rates for an increased number of users with enhanced reliability for a greater range of coverage. The frequency spectrum is a major constraint of a wireless system. In modern communication systems, a high speed data rate with better security is required with a large coverage area in a constrained environment of limited frequency spectrum. MIMO is capable of meeting this requirement [2]. A multiple-antenna system serves the different purposes of a high-speed wireless network. It enhances the instantaneous signal-to-noise ratio, using techniques like beamforming to reduce the ergodic error probability, which results in improved link reliability [3]. A multiple-antenna system is also suitable for reducing the variations of the SNR, using diversity For a very high data rate and a better link reliability, instead of few antenna units, a large array of antenna elements is mounted at the base station in a massive MIMO system. This is a totally different configuration of BTS design as compared to the current standards, in which a maximum of 8 antennas are used in a sectored topology. Active antenna units in huge numbers are used to focus the energy continuously towards the User Equipment (UE), in target, with the help of different precoding schemes. As a result, the requirement of radiated power and the interference among different users is reduced [4]–[6]. However, a large number of antennas mounted at a particular site poses several challenges for massive MIMO Systems that are completely different from the often arising problems of trivial networks. For example, in LTE or LTE-Advance, the pilot overhead should be comparable to the numerical figure of antenna units. In massive MIMO systems this overhead will be very large due to the hefty amount of antenna elements but it is managed with the proper use of channel reciprocity between the uplink and the downlink in TDD [7]. In channel reciprocity, the Channel State Information (CSI) acquired from the pilots used in uplink transmission is utilized for the downlink precoder. The practical implementation of massive MIMO systems requires synchronization among a large number of independent RF transceivers and scaling of data buses by an order of magnitude or more which are additional challenges to be encountered [8]. A massive MIMO system constitutes a cellular network with an improved spectrum and energy efficiency The benefits of a massive MIMO system can be enjoyed if the accuracy of CSI is maintained at both the downlink and the uplink (that is, both at BTS and UE). CSI is very important characteristic of a communication system. In massive MIMO, the quality of service (QoS) depends on the accuracy of the CSI. There are two main reasons for inaccuracy in the CSI in massive MIMO systems, known as channel estimation error and channel aging [9]. A comparative study of BF and regularized zero forcing (RZF) for TDD downlink massive MIMO gives results for path loss, channel estimation, pilot contamination and arbitrary antenna [10], [11]. T. E. Bogale (2014) proposed hybrid beamforming for MU-massive MIMO systems at the downlink. The proposed beamforming, which is a combination of analog and digital

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beamforming, is based on the WSMSE minimization problem, which is resolved by using the theory of compressed sensing [12]. Yue, D. W. and Li, G. Y. (2014) proposed transmit-and-receive conjugate beamforming, which is a transmission scheme based on line-of-sight (LOS) to get rid of problems generated by contaminated pilots. It reduces the overhead required for full CSI. In the proposed conjugate beamforming precoding scheme, the scattered component of the signal is considered as an interference over Rician flat fading channel environment [13]. Park, C. S. *et al.*(2014) proposed a ZF-BF scheme with a reduced complexity based on sequential inter-beam interference cancellation in a descending order of their strength. The results obtained from analysis show that as the number of inter-beam interference cancellations increases, the performance of the projected scheme shifts towards that of ZF-BF [14]. Lakshminarayana, S. *et al.* (2015) proposed a multi-cell beamforming algorithm for massive-MIMO systems, based on the random matrix theory, with a very limited exchange of information about the channel statistics instead of complete CSI between the two BTSs, to minimize the requirement of the total transmit power for each base station [15]. In the present study, MIMO with different equalization techniques is considered as a key solution for a bandwidth-proficient transmission technique for wireless communication. The proposed study reduces the interference and increases the capacity of the system with the least BER.

II. System Model

Consider a massive MIMO system with multiple receiver antennas and multiple antennas at the transmitter. Let us assume that all the antennas are uncorrelated.

A. Mathematical Model

The implementation of MIMO results in increased throughput due to MIMO systems and flat fading is achieved. A frequency-selective MIMO channel can be written mathematically as follows [16]:

$$\bar{z}(t) = H(0)\bar{s}(t) + H(1)\bar{s}(t-1) + H(2)\bar{s}(t-2) + \cdots + H(L-1)\bar{s}(t-L+1) + \bar{n}, \quad (1)$$

where
$\bar{s}(t)$ – Tx vector at time t;
$\bar{s}(t-1)$ – Tx vector at time t − 1;
$H(L)$ – $N \times M$ channel matrix;
$\bar{n}(t)$ – noise.

In a frequency-selective MIMO channel, ISI occurs between the current and previously transmitted symbol vectors. To overcome this problem, IFFT operation is performed for each transmitting antenna. A MIMO-OFDM system converts a frequency-selective MIMO channel into a group of multiple parallel flat-fading MIMO channels. The M-parallel flat-fading MIMO channels can be expressed mathematically as

$$\bar{z}(0) = \bar{H}(0)\bar{s}(0); \quad (2)$$

$$\bar{z}(1) = \bar{H}(1)\bar{s}(1); \quad (3)$$

$$\bar{z}(N-1) = \bar{H}(M-1)\bar{s}(M-1). \quad (4)$$

In general, it can be written as:

$$\bar{z}(k) = \bar{H}(k)\bar{s}(k), \quad (5)$$

where,

$\bar{z}(k)$ – Rx 1 receive vector to subcarrier *k*;

$\bar{H}(k)$ – flat fading channel matrix;

$\bar{s}(k)$ – Tx 1 transmit vector to subcarrier *k*.

Each of $\bar{z}(k)$ can be processed by a simple MIMO-ZF receiver or a MIMO-MMSE receiver for detecting vector $\bar{s}(k)$.

B. Detection of Signal

To observe the anticipated signal from the objective transmit aerial at the reception end, all the interference signals are nullified or minimized by inverting the effect of the channel by multiplying a suitable weight matrix $\bar{W}$, such that [17]:

$$\tilde{Y} = [\tilde{y}_1, y_2, \ldots, y_{N_T}]^{\mathrm{T}} = \bar{W}\bar{X}, \quad (6)$$

i.e. each detected symbol is represented by a linear combination of received signals.

C. Zero Forcing Signal Detection

In zero forcing signal detection the interferences are nullified by weight matrix W_{ZF}, where

$$ZF_{\mathrm{ZF}} = (H^{\mathrm{T}}H)^{-1}H^{\mathrm{T}}. \quad (7)$$

It inverts the effect of the channel as

$$\tilde{X}_{\mathrm{ZF}} = ZFE_{\mathrm{ZF}}Y = \quad (8)$$

$$= \bar{X} + (H^{\mathrm{T}}H)^{-1}H^{\mathrm{T}}\bar{\sigma} = \quad (9)$$

$$= \bar{X} + \bar{\sigma}_{\mathrm{ZF}}, \quad (10)$$

where, $\bar{\sigma}_{\mathrm{ZF}} = W_{\mathrm{ZF}}\bar{\sigma} = (H^{\mathrm{T}}H)^{-1}H^{\mathrm{T}}\bar{\sigma}$.

The noise power can be calculated as $\|\bar{\sigma}_{\mathrm{ZF}}\|_2^2$.

The expected value of noise power is as follows:

$$E\{\|\bar{\sigma}_{\mathrm{ZF}}\|_2^2\} = \sum_{i=1}^{N_r} \frac{\sigma_{\mathrm{nt}}^2}{\sigma_{\mathrm{it}}^2}. \quad (11)$$

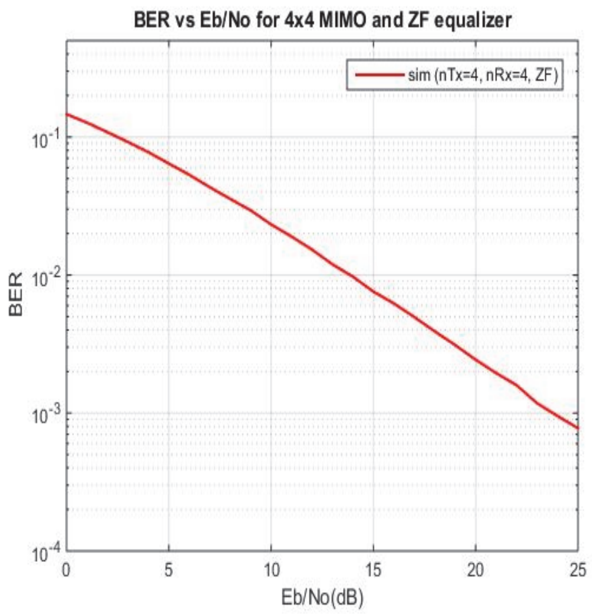

Fig. 1. Zero forcing BER vs E_b/N_o MMSE signal detection.

D. Minimum Mean Square Error

In the proposed signal detection, the interference is reduced by improving the post-recognition of signal-to-interference plus noise ratio (SINR) by enlarging the received signal with a MMSE weight matrix, given as [18]:

$$V_{\mathrm{MMSE}} = (H^H H + N_n^2 i)^{-1} H^{\mathrm{T}}. \quad (12)$$

It reduces the noise by reversing the channel outcome as

$$\bar{Y}_{\mathrm{MMSE}} = V_{\mathrm{MMSE}} \bar{X} = \quad (13)$$

$$= (H^{\mathrm{T}} H + N_n^2 I)^{-1} H^{\mathrm{T}} \bar{X} = \quad (14)$$

$$= \bar{Y} + (H^{\mathrm{T}} H + N_n^2 i)^{-1} H^N \overline{ns}; \quad (15)$$

$$\bar{Y}_{\mathrm{MMSE}} = \bar{Y} + \overline{ns}_{\mathrm{MMSE}}, \quad (16)$$

where $\overline{ns}_{\mathrm{MMSE}} = (H^{\mathrm{T}} H + N_n^2 I)^{-1} H^{\mathrm{T}} \overline{ns}$.

The noise power can be calculated as $\|\overline{ns}_{\mathrm{MMSE}}\|_2^2$. The expected value of the noise power is as follows:

$$\mathrm{E}\{\|\overline{ns}_{\mathrm{MMSE}}\|_2^2\} = \sum_{i=1}^{N_T} \frac{\sigma_m^2 \sigma_{ni}^2}{(\sigma_{ni}^2 + \sigma_m^2)^2}. \quad (17)$$

The results for BER using 4 × 4 MMSE detection are given below.

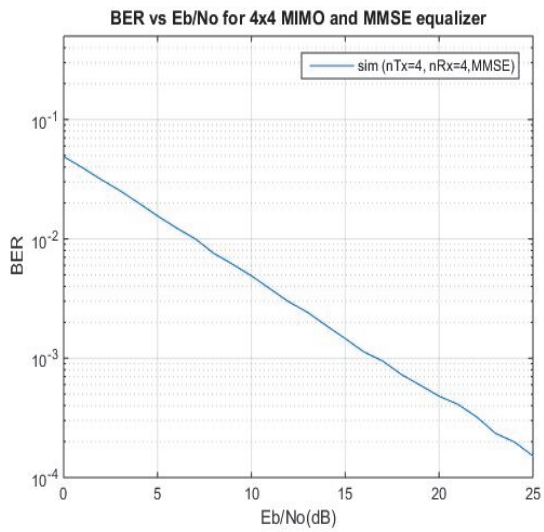

Fig. 2. BER vs E_b/N_o for 4 × 4 MIMO-MMSE detector.

E. Beamforming

In the beamforming signal detection technique we use a closed-loop transmission diversity scheme, where the channel is already known to the receiver. In this method the receiver sends feedback about the channel information to the target transmitter. To minimize the effect of the channel, the symbol transmitted from each transmission antenna is multiplied by a complex number, which is equal to the inverse of the phase of the channel, so that all the received signals at a receiver lead to constructive interference.

Mathematically, the received signal (without BF) is as follows:

$$\bar{X} = HY + \bar{\sigma} =$$
$$= \bar{h}_1 y_1 + \bar{h}_2 y_2 + \cdots + \bar{h}_{N_T} y_{N_T} + \bar{\sigma}. \quad (18)$$

The received signal with BF can be expressed as follows:

$$x = \begin{bmatrix} h_1 h_2 h_3 \ldots h_{N_T} \end{bmatrix} \begin{bmatrix} \exp^{-j\theta 1} \\ \exp^{-j\theta 2} \\ \exp^{-j\theta 3} \\ . \\ . \\ . \\ \exp^{-j\theta N_T} \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ . \\ y_{N_T} \end{bmatrix} + \sigma, \quad (19)$$

where $h_i = |h_i| \exp^{j\theta i}$.

Thus, the signal received at the receiver is

$$x = (|h_1| + |h_2| + \cdots + |h_{N_T}|) y + \sigma. \quad (20)$$

To invert the effect of the channel, the received symbols are multiplied by the inverse of the channel matrix obtained using beamforming. The detected symbol can be expressed mathematically as

$$\tilde{x} = \frac{yx}{(|h_1|+|h_2|+\cdots+|h_{N_T}|)} = \\ = y + \frac{n\sigma}{(|h_1|+|h_2|+\cdots+|h_{N_T}|)}. \quad (21)$$

For a 4 × 1 MIMO system, the simulation results for BER using BF equalization are given below. BER decreases with the increase of SNR.

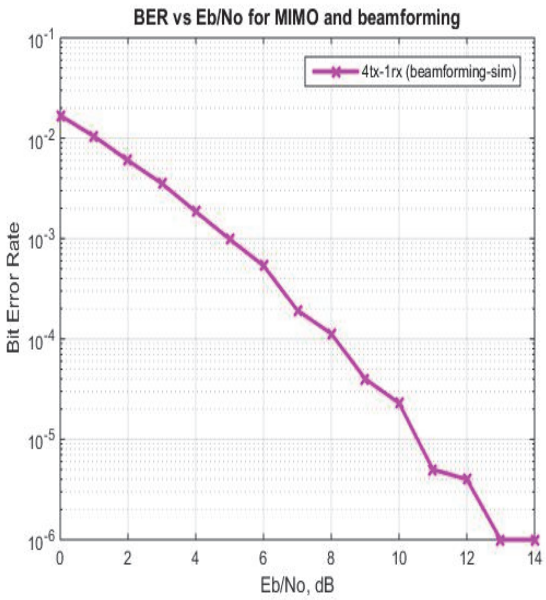

Fig. 3. BER vs E_b/N_o for 4 × 1 BF detector.

The results for 8 × 1, BER using BF detection, are given below. The graph shows that BER decreases with the increase of SNR.

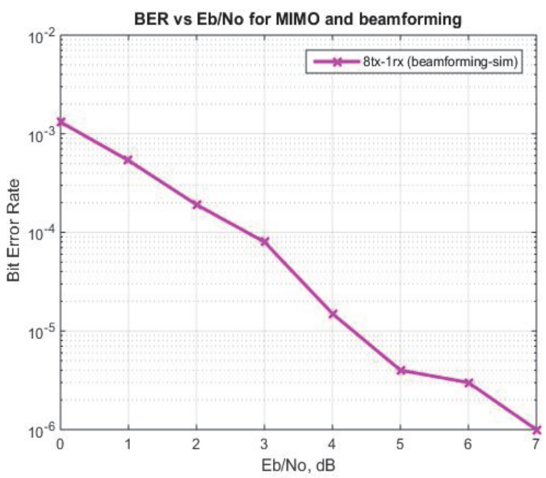

Fig. 4. BER vs E_b/N_o for 8 × 1 BF detection.

In our observations we designed an 8 × 1 MIMO system without using the beamforming technique for signal detection at the receiver. The results obtained are very interesting. For an 8 × 1 MIMO system, the results for BER vs SNR are given below in Fig. 5: for cases with and without beamforming detection schemes. It can be concluded that the performance of the system is dramatically improved by the use of a beamforming signal detection scheme at the receiver.

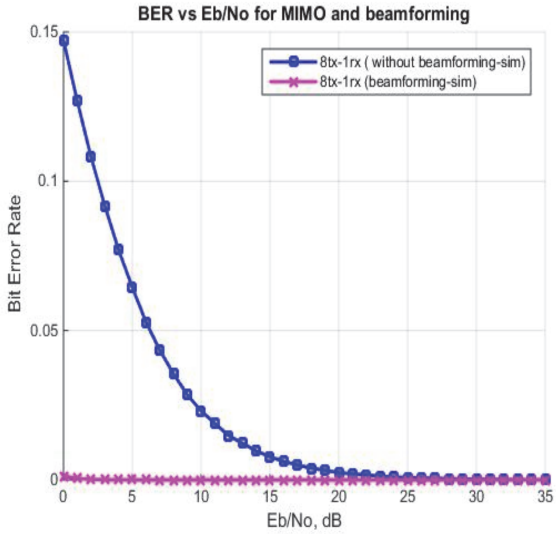

Fig. 5. BER vs E_b/N_o for 8 × 1 MIMO systems with and without beamforming.

III. Results and Discussion

Simulation results for 4 × 4 MIMO systems, using three different equalization techniques (ZF, MMSE and beamforming), are analyzed to obtain the behaviour of their performances based on BER. Zero forcing equalization is trying to nullify the interference and provides a moderate BER value for higher SNR as it is easy to implement practically due to lesser complexity. The simulation results show that MMSE is a comparatively better technique for post-detection equalization. Tabular values show that MMSE provides the least BER for moderate SNR values. However, it is comparatively complex to design and implement practically. Another technique called beamforming is used here to minimize the interferences and enhance system performance. The simulation has tremendously positive results for beamforming. For higher SNR, an almost-zero BER is observed for large amounts of transmitting bits. The simulation results for the 8 × 1 MIMO show that BER is considerably reduced even at a lower SNR if beamforming is used.

IV. Conclusion

MIMO is a multiple-antenna system consisting of a huge number of antennas at both the transmitter and receiver ends. It provides an improved data transmission rate as compared to the conventional single-antenna system used in sectored topology. However, it is not sufficient for the ever-increasing demands of much better data rates. For further improvement in communication systems, multiple-carrier systems like OFDM are integrated with a multiple-antenna system, MIMO. It yields very enthusiasm-provoking results, yet with certain limitations regarding practical implementations. While implementing MIMO-OFDM practically, it requires a huge amount of power. A high PAPR is associated with MIMO-OFDM systems, which is a disadvantage because it requires sophisticated RF components, which are costly. The design of a MIMO-OFDM System must appropriately address the issue of PAPR reduction. Fourth-generation (4G) communication systems use contemporary technologies like multiuser-MIMO and MIMO-OFDM. For next generation wireless communication systems (5G) massive-MIMO is a better choice over other technologies. In this technology, large numbers of antenna arrays are mounted at base stations with as much separation among antenna elements as practically possible. This study focuses on the implementation of zero forcing (ZF), minimum mean square error (MMSE) and beamforming (BF) in a MIMO system. The results show that ZF is the simplest technique for signal detection; however, beamforming (BF) provides improved bit error rate (BER) performances at high signal-to-noise ratio (SNR) values. For more antennas at the base station, it is too complex to design the weight matrix for ZF, however, it is suitable for BF with the help of good-quality digital signal processors. The performance of a MIMO system, with 8 antennas at the base station, using BF equalization, is analysed to get BER values at different values of SNR. The results show a considerable improvement in BER for 8 antennas at the base station. In the future, we will be living in a digital world where our daily needs will largely be dependent on digital data of various kinds. To fulfil the demands of high-speed data in real-time access, a very high speed data transfer network will be a necessity. To achieve this, an entire new system of next-generation communication will be required. For this we can simulate a further-improved model of a multi-antenna system, which is capable of addressing the practical implementation problems for next-generation cellular communication systems. As we know, the number of antennas at the user terminal cannot be increased beyond a certain limit due to design constraints, hence the future work will be focused on increasing the number of antenna units at the base station using a variety of signal detection techniques (like beamforming). The use of millimeter waves in massive MIMO systems, cognitive radio integrated with massive MIMO Systems and multi-carrier transmission like universal filter multi-carrier (UFMC)with multiple antenna systems are promising future technologies, which will reduce the bandwidth requirements and provide a considerably improved QoS.

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References

[1] W. D. Bliss, K.W. Forsythe, and M. A. Chan, "MIMO Wireless Communication," *Lincoln Laboratory Journal*, vol. 15, no.1, pp. 97–126, 2005.

[2] T. Yasodha, "Decoding for 8×8 MIMO System Using Convolution Coding Implemented in VLSI," *Int. J. Eng. Res. Appl.*, vol. 3, no. 1, pp. 278–282, Jul.–Aug. 2013.

[3] J. Hoydis, C. Hoek, T. Wild, and S. ten Brink, "Channel Measurements for Large Antenna Arrays," *Proc. Int. Symp. Wireless Communication. Syst. (ISWCS)*, pp. 811–815, Aug. 2012. https://doi.org/10.1109/iswcs.2012.6328480

[4] E. Bjornson, J. Hoydis, M. Kountouris, and M. Debbah, "Massive MIMO Systems With Non-Ideal Hardware: Energy Efficiency, Estimation, and Capacity Limits", *IEEE Transactions on Information Theory*, vol. 60, no. 11, pp. 7112–7139, Nov. 2014. https://doi.org/10.1109/tit.2014.2354403

[5] K. Sengar, N. Rani, A. Singhal, D. Sharma, S. Verma, and T. Singh, "Study and Capacity Evaluation of SISO, MISO and MIMO RF Wireless Communication Systems," *Int. J. Eng. Trends Technology (IJETT)*, vol. 9, no. 9, pp. 437–440, Mar. 2014. https://doi.org/10.14445/22315381/ijett-v9p283

[6] D. Zhu, B. Li, and P. Liang, "On the Matrix Inversion Approximation Based on Neumann Series in Massive-MIMO Systems," *IEEE ICC - Wireless Communication Symposium*, pp. 1763–1769, Jun. 2015. https://doi.org/10.1109/icc.2015.7248580

[7] A. Kumar and M. Gupta, "Design of 4:8 MIMO OFDM With MSE Equalizer for Different Modulation Techniques," *Wireless personal Communication*, vol. 95, no. 4, pp. 4535–4560, Mar. 2017. https://doi.org/10.1007/s11277-017-4099-1

[8] A. Kumar and M. Gupta, "Design and Performance Evaluation of MB-MIMO-UWB for Different Transmission Techniques," *Proc. Natl. Acad. Sci., India, Sect. A Phys. Sci*, 2017. https://doi.org/10.1007/s40010-017-0400-7

[9] A. Kumar and M. Gupta, "Design, Development of MC-CDMA, and Reduction of ISI for Different Modulation Techniques," *Proc. Int. Conf. on Recent Cognizance in Wireless Communication and Image Process*, pp. 81–91, 2016. https://doi.org/10.1007/978-81-322-2638-3_9

[10] A. Kumar and M. Gupta, "Design, Comparative Study and Analysis of CDMA for Different Modulation Techniques," *Egyptian Informatics Journal*, vol. 16,no. 3, pp. 351–365, 2015. https://doi.org/10.1016/j.eij.2015.07.004

[11] X. Gao, O. Edforce, F. Rusek, and F. Tufvesson, "Massive MIMO Performance Evaluation Based on Measured Propagation Data," *IEEE Transactions on Wireless Communication*, vol. 14, no. 7, pp. 3899–3911, Jun. 2015. https://doi.org/10.1109/twc.2015.2414413

[12] T. L. Marzetta, "Noncooperative Cellular Wireless With Unlimited Numbers of Base Station Antennas," *IEEE Transaction on Wireless Communication*, vol. 9, no. 11, pp. 3590–3600, Nov. 2010. https://doi.org/10.1109/twc.2010.092810.091092

[13] D. W. Yue and G. Y. Li, "LOS-Based Conjugate Beamforming and Power-Scaling Law in Massive-MIMO Systems," *arXiv preprint*, arXiv:1404.1654, Dec. 2014.

[14] C.-S. Park, Y.-S. Byun, A. M. Bokiye, and Y.-H. Lee, "Complexity Reduced Zero-Forcing Beamforming in Massive MIMO Systems," *Information Theory and Applications Workshop (ITA)*, pp. 1–5, Feb. 2014.

[15] S. Lakshminarayana, M. Assaad, and M. Debbah, "Coordinated Multicell Beamforming for Massive MIMO: A Random Matrix Approach," *IEEE Transactions on Information Theory*, vol. 61, no. 6, pp. 3387–3412, Jun. 2015. https://doi.org/10.1109/tit.2015.2421446

[16] Z. Gao, L. Dai, W. Dai, and Z. Wang, "Block Compressive Channel Estimation and Feedback for FDD Massive MIMO," *Computer Communications Workshops (INFOCOM WKSHPS), 2015 IEEE Conference*, pp. 49–50, Apr. 2015. https://doi.org/10.1109/infcomw.2015.7179337

[17] Y. Han, J. Ni, and G. Du, "The Potential Approaches to Achieve Channel Reciprocity in FDD System With Frequency Correction Algorithms," *Proc. Int. ICST Conf. Commun. Netw.*, pp. 143–149, 2010. https://doi.org/10.4108/chinacom.2010.154

[18] J. Hoydis, S. ten Brink, and M. Debbah, "Massive MIMO: How Many Antennas Do We Need?," *IEEE 49th Annual Allerton Conference on Communication, Control, and Computing (Allerton*), pp. 545–550, Sep. 2011. https://doi.org/10.1109/allerton.2011.6120214

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