Effect of NR-LDPC Codes on the Uplink Massive MIMO

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Abstract

Future wireless communication technologies and the current fifth generation (5G) mobile communication system will need to provide greater coverage, spectral efficiency and reliability with reduced data traffic congestion. However, in wireless communication, reaching these objectives presents difficulties. Therefore, using only massive multiple-input multiple-output (M-MIMO) technology will not be sufficient to meet the continuously increasing demand, guarantee high reliability and avoid data traffic congestion. In this paper, the performance of M-MIMO system concatenated with channel coding using the low-density parity-check codes described in the Third Generation Partnership Project (3GPP) technical specification TS 38.212 is investigated. The performance is evaluated and comparisons are made in terms of bit error rate (BER) as a function of the signal to noise ratio (SNR) for different linear receivers: maximal ratio combiner (MRC), zero-forcing (ZF) and minimum mean square errors (MMSE). In addition, a comparison for the coded and uncoded M-MIMO in the uplink (UL) using these receivers are made. MMSE and ZF showed the best simulation results across all scenarios; however, MRC needed a notably greater number of antenna elements to match their performance.

Keywords: Channel coding, 5G, LDPC codes, massive MIMO, BER.

Introduction

Due to the explosive rise in popularity of smartphones, laptops, tablets and other wireless devices with high data consumption, data traffic—both fixed and mobile—has increased dramatically in recent years. Future demand is predicted to rise much higher for cellular data transmission. The improvements in system performance and the widespread adoption of new applications and device types will cause a sharp increase in the number of mobile subscriptions worldwide in the future. Global mobile subscriptions are expected to reach 13.8 billion in 2025 and 17.1 billion in 2030, respectively (ITU-R, 2015).

Area throughput is a crucial performance metric for both current and future cellular networks. The area throughput, expressed in bit/second/km^2 (bps/km^2), can be modeled using Equation 1.

$$\text{Area throughput} = B_W(Hz) * D_c\ (cells/km^2) * SE\ (bits / s/ Hz/ cell) \quad (1)$$

where B_W is the bandwidth, D_c is the mean cell density and SE is the spectral efficiency (Marzetta *et al.*, 2016; Björnson *et al.*, 2017). The issue with expanding bandwidth to boost throughput and capacity is that much of the world lacks sufficient spectrum, particularly in the 700 MHz to 2.6 GHz region below 6 GHz (Rappaport et al., 2013; Gahadza and Winberg, 2019). In addition to the cost of new equipment, rentals, power costs and operational and capital expenditures (OPEX and CAPEX), network densification to improve site capacity has the disadvantage that any gains made are generally offset by an increase in network interference (Hoydis et al., 2011). M-MIMO is one of the primary technologies that enables 5G and beyond networks to give high spectral and energy efficiency (Chataut and Akl, 2020).

To enhance the system's reliability in current era of communication technology, it is preferable to raise the data rate while minimizing error (Bhardwaj, Mishra and Shankar, 2022). Channel coding is one of the communication technologies for error detection and correction that can greatly increase communication system reliability and guarantee effective transmission (Zhao, Tian and Xue, 2019). Various research works have assessed the M-MIMO system's performance when combined with channel coding. Chen et al. (Chen, Lin and Ueng, 2016) explored generalized space shift keying (GSSK) concatenated with LDPC decoder using codebook-assisted hard decision (CAHD) and soft decision (CASD) detector over 128x8 M-MIMO system. Stanciu and Voicu (Stanciu and Voicu, 2018) evaluated the BER performance of an M-MIMO system in the uplink scenario utilizing convolutional LDPC coding. Hwang et al. (Hwang, Park and Lee, 2019) evaluated a coded MIMO system with iterative joint detecting and decoding (JDD) using conventional LDPC codes and low complexity detection. Tummala and Korrai (2020) suggested employing ZF, MMSE and approximate message passing (AMP) equalizers for M-MIMO systems. The irregular Gallager codes were used to construct the parity check matrix (PCM) for the LDPC code. Marques et al (Marques da Silva, Dinis and Martins, 2021) investigated power-ordered techniques employing the QC-LDPC codes of the 5G standard for cooperative and traditional Non-Orthogonal Multiple Access (NOMA) over M-MIMO system. Park and Lee (Park, H. J. and Lee, 2022) developed an iterative joint detecting and decoding (JDD) approach to create an LDPC coded multi user (MU) M-MIMO system. None of the research mentioned above took into account linear receivers MRC, ZF and MMSE for M-MIMO with quasi-cyclic (QC) LDPC codes, especially the 5G NR (new radio) LDPC codes described in TS 38.212. For this reason, the impact of various antenna elements at the base station (BS) on the BER of active users is examined in this paper for the three linear receivers. Furthermore, assess the BER performance of coded M-MIMO with uncoded in the UL direction.

Methodology

Since the current and future wireless communication systems should support a wide range of services and applications, the user data blocks will vary in length. Therefore, the 3GPP adopted the NR-LDPC with a refined structure that sets them apart from earlier standards. Many wireless communication standards, including IEEE 802.16e (WiMAX), IEEE 802.11n, and Digital Video Broadcast/ Satellite Second Generation (DVB-S2), have used the LDPC codes as channel coding (Indoonundon and Pawan Fowdur, 2021; Nguyen, Tan and Lee, 2021). For example, there are 12 distinct codes that make up the 802.11 codes, each with a description (Richardson and Kudekar, 2018). The quasi-cyclic (QC-LDPC) codes that make up the NR-LDPC codes are characterized by two base graphs (BGs) with comparable structural features. BG1 is intended for code rates R ($^1/_3 \leq R \leq {}^8/_9$) and blocks of lengths ($500 \leq \text{Ꮶ} \leq 8448$). The mother code rate of BG2 is 1/5 and it is intended for short blocks of lengths ($40 \leq \text{Ꮶ} \leq 3840$) with lower rates ($^1/_5 \leq R \leq {}^2/_3$). Figure 1 shows the BGs structure diagram for NR-LDPC codes.

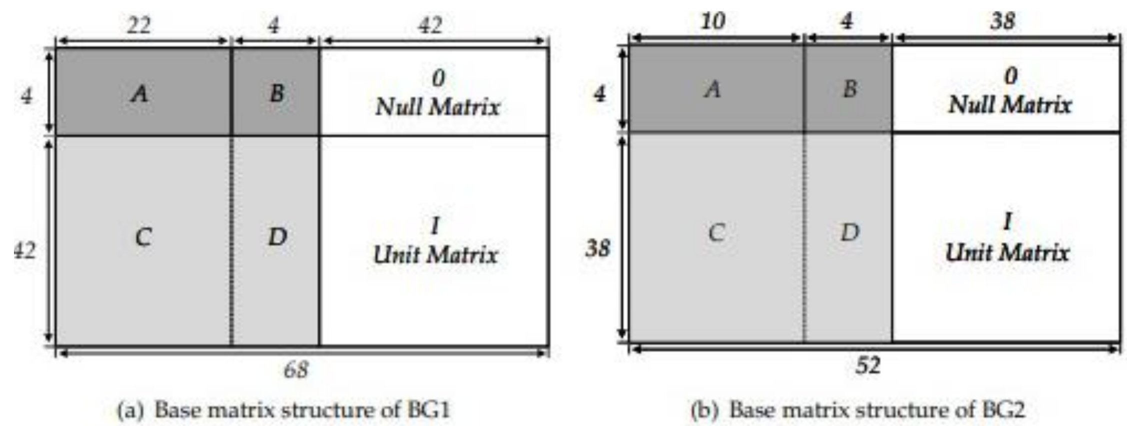

Figure 1: BGs structure diagram for NR-LDPC codes(Tian, Bai and Liu, 2021).

Eight distinct lifting size sets are defined for each BG as $Z_c = a.2^j$, where the constant a defines the lifting-size and $a \in \{2, 3, 5, 7, 9, 11, 13, 15\}$ and $0 \leq j \leq 7$ as shown in **Table** 1.

Table 1: Relation between sets of Z_cs and exponent matrices.

Set index (i_{LS})	Exponent Matrix	Lifting Size Set
0	$\boldsymbol{P_1(a = 2)}$	$Z_c = 2.2^j, j = 0,1,2,3,4,5,6,7$
1	$\boldsymbol{P_2(a = 3)}$	$Z_c = 3.2^j, j = 0,1,2,3,4,5,6,7$
2	$\boldsymbol{P_3(a = 5)}$	$Z_c = 5.2^j, j = 0,1,2,3,4,5,6,$
3	$\boldsymbol{P_4(a = 7)}$	$Z_c = 7.2^j, j = 0,1,2,3,4,5$
4	$\boldsymbol{P_5(a = 9)}$	$Z_c = 9.2^j, j = 0,1,2,3,4,5$
5	$\boldsymbol{P_6(a = 11)}$	$Z_c = 11.2^j, j = 0,1,2,3,4,5$
6	$\boldsymbol{P_7(a = 13)}$	$Z_c = 13.2^j, j = 0,1,2,3,4$
7	$\boldsymbol{P_8(a = 15)}$	$Z_c = 15.2^j, j = 0,1,2,3,4$

The scenario in this paper is that a single cell with a BS equipped with M serving antennas and K single-antenna devices are assumed to be in the uplink. **Figure** 2 shows the system model to improve the BER of the M-MIMO system. The LDPC encoding chain was set depending on the TS 38.212. The LDPC decoding process for the 5G NR shared channels is not described in 3GPP TS 38.212, despite the fact that it specifies the LDPC encoding chain. Therefore, the layered belief propagation with 25 maximum iteration is used as a decoding algorithm according to the results of (Salih, Al-Qaradaghi and Ameen, 2022).

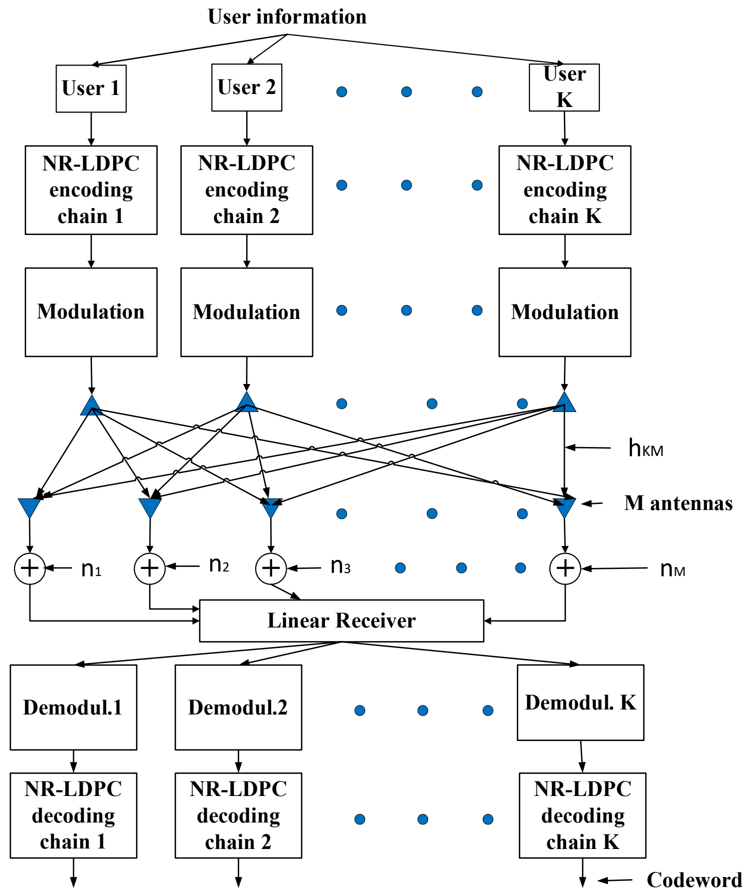

Figure 2: The M-MIMO system model to improve BER.

To compute BER, the bit stream produced at the output of each LDPC decoder is compared to the corresponding input sequence. The parameters of the simulation are summarized in **Table** 2.

Table 2: Simulation parameters**.**

Parameter	**Setting**
Message length (frame)	64 bits
Coding rate	½
Decoder type	Layered Belief Propagation (LBP)
Maximum number of iterations	25
Modulation method	Quadrature phase shift keying (QPSK)
Number of active users	10
Number of BS serving antennas	20,50,90,120,200
Channel	Rayleigh
Detection method	MRC, ZF, MMSE

In the case of uplink (also known as reverse link) transmission, K users send signals to the BS.

A perfect channel state information (CSI) is assumed at the receiver of the M-MIMO system. The M x1 received vector at the BS in the UL is:

$$\boldsymbol{y} = \sqrt{p_u}\ \sum_{k=1}^{K} \boldsymbol{h}_k\, x_k + \boldsymbol{n} \tag{2}$$

$$= \sqrt{p_u}\, \boldsymbol{Hx} + \boldsymbol{n} \tag{3}$$

where the transmitted signal from the k[th] user is indicated by $\sqrt{p_u}\, x_k$ (each user transmits power on average of p_u), $\boldsymbol{h}_k \in \mathbb{C}^{M\times 1}$ indicates the channel vector that links the k[th] user to the BS, $\boldsymbol{n} \in \mathbb{C}^{M\times 1}$ represents the vector of additive noise, $\boldsymbol{H} \triangleq [\boldsymbol{h}_1\ \ldots\ \boldsymbol{h}_K]$ is an $M \times$ K matrix corresponds to the fast fading coefficients between the K terminals and the BS serving array and $\boldsymbol{x} \triangleq [x_1\ \ldots\ x_K]^{\boldsymbol{T}}$.

The received signal $\tilde{y}$ is multiplied by a M × K conjugate-transpose of a linear detection matrix (A) at the BS using linear detection techniques, resulting in the separation of K streams as follows

$$\widehat{\boldsymbol{y}} = \boldsymbol{A}^H\, \boldsymbol{y} \tag{4}$$

Three linear detectors, namely MRC, ZF and MMSE with linear detection matrices defined by equation (5) are used (Ngo, Larsson and Marzetta, 2013)

$$\boldsymbol{A} = \begin{cases} \boldsymbol{H}^H & for\ MRC \\ (\boldsymbol{H}^H\boldsymbol{H})^{-1}\boldsymbol{H}^H & for\ ZF \\ \boldsymbol{H}^H(\boldsymbol{H}\boldsymbol{H}^H + \sigma_n^2\, \boldsymbol{I})^{-1} & for\ MMSE \end{cases} \tag{5}$$

To optimize the received SNR for each stream, the BS employs MRC. Thus, by scaling the received signal $\boldsymbol{y}$ by the conjugate-transpose of the channel's vector $\boldsymbol{h}_k$, the transmitted signal from the k[th] user is identified as

$$\tilde{y}_k = \boldsymbol{h}_k^H\, \boldsymbol{y} = \sqrt{p_u}\, \|\boldsymbol{h}_k\|^2\, x_k + \sqrt{p_u}\ \sum_{i\neq k}^{K} \boldsymbol{h}_k^H \boldsymbol{h}_i x_i + \boldsymbol{h}_k^H\, \boldsymbol{n} \tag{6}$$

$(.)^H$ represents the Hermitian operator (conjugate-transpose of a vector/matrix).

By simply multiplying the received vector by the conjugate-transpose of the channel matrix $\boldsymbol{H}$ and then uniquely identifying each stream, the BS performs simple signal processing. ZF uses the noisy received signals to approximate the transmitted ones. The error squared between the signals that are sent and received is reduced by using this technique. Since the MMSE uses a Bayesian technique to estimate the signal vector $\widehat{\boldsymbol{x}}$, the transmitted vector $\boldsymbol{x}$ is regarded as random. Therefore, the MMSE receiver minimizes the mean or average of the squared error.

Results and Discussions

Ten users with single antenna devices were chosen in order to evaluate the system's performance with a variety of serving BS antennas. SNRs for users have been tested to range from -4 to 14 dB. **Figure** 3 shows the BER as an SNR indication when employing MRC. Multiuser interference can be significantly reduced by utilizing very large antenna arrays (M >> K), which explains why the BER reduces as the number of BS antennas increases. Every receiving antenna captures a slightly different version of the transmitted signal due to the varying paths taken by the signal throughout its transmission. The MRC receiver is able to take advantage of this spatial variety. The signals with greater quality (higher SNR) are combined by the MRC receiver according to their weight. By reducing the impact of noise and fading on the received signal, this weighted combination improves the overall quality of the signal. The power of the received signal increases linearly with the number of receiving antennas. By decreasing the effects of noise and interference, this increased signal strength can lower the BER.

At BER = $1x10^{-5}$, **Figure** 3 shows that there is an approximately 6 dB SNR gain between the scenarios where 90 and 200 BS antennas serve 10 active users.

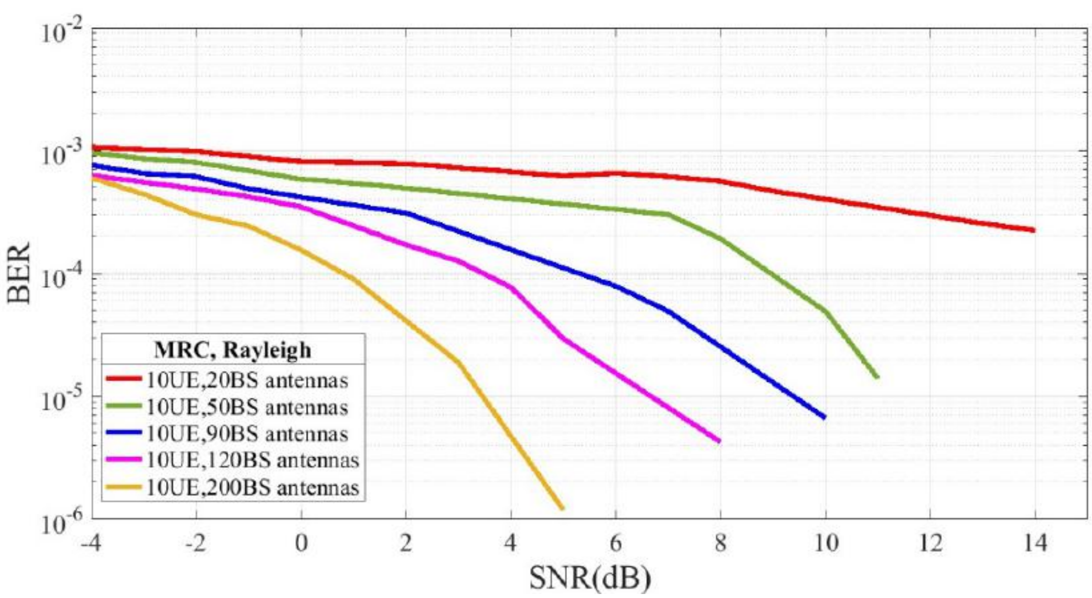

Figure 3: BER of the M-MIMO system with various BS antennas utilizing MRC detection.

The ZF receiver can efficiently isolate and decode multiple user signals if it has more antennae. ZF is intended to remove interference between users. It achieves this by essentially isolating the desired user's signal by canceling out the interference from other users. Furthermore, diversity gain from many antennas lessens the effects of fading and multipath propagation. **Figure** 4 shows the BER as an SNR indication for different numbers of BS antennas when ZF is used. The BER decreases with increasing BS antenna number. For instance, as **Figure** 4 illustrates, at BER = $1x10^{-4}$, there is an SNR gain of approximately (10, 12 and 14) dBs between the scenarios with 20 and (90, 120 and 200) BS antennas, respectively.

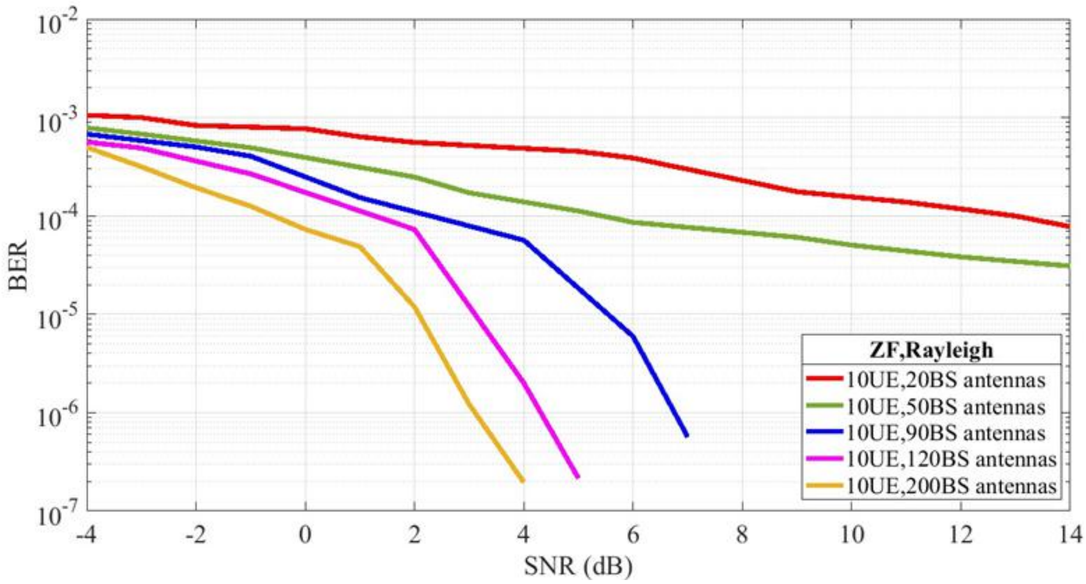

Figure 4: BER of the M-MIMO system with ZF detection for various BS antennas.

As shown in **Figure** 5, the proposed system has been evaluated and tested using an MMSE receiver with the same parameter values as those in Table 2. **Figure** 5 shows the BER for different numbers of BS antennas when MMSE is used. The BER decreases when the total number of BS antennas is increased. For instance, as illustrated in **Figure** 5, between the cases where there are 20 and 90 antennas serving ten active users, there is an SNR gain of approximately 8 dBs at BER = $1x10^{-4}$, 7.8 dBs at BER = $1x10^{-5}$ and 6.5 dBs at BER = $1x10^{-6}$. Having more antennas serving a similar number of users at the BS results in higher benefits for SNR.

The MMSE receiver takes into consideration the spatial relationship between antennas and channel conditions in order to minimize mean square error. It is effective in reducing both multipath and other user interference. The MMSE receiver can minimize interference from other users with greater spatial degrees of freedom when it has more receiving antennas installed. Better interference mitigation results from this, which lowers the BER.

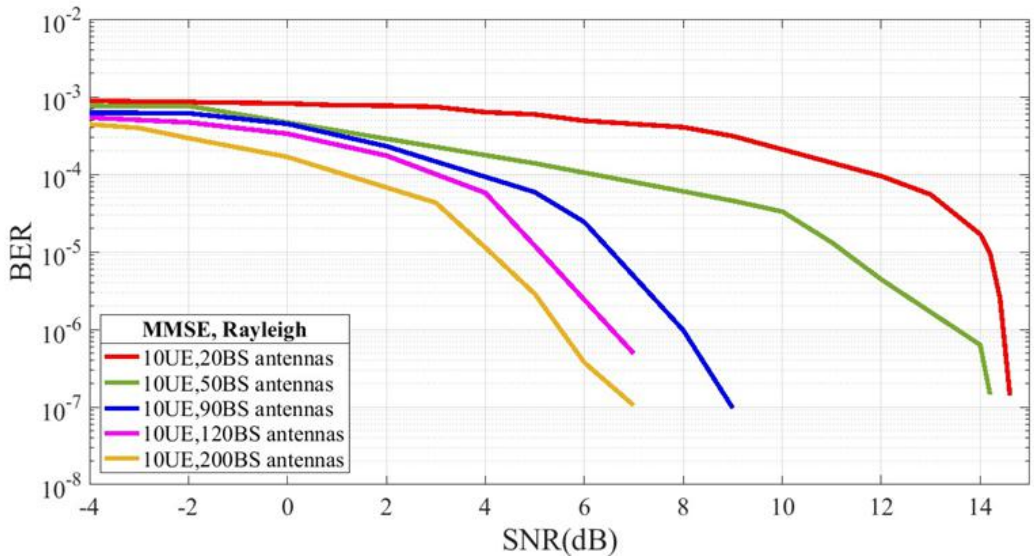

Figure 5: BER of M-MIMO system with varying base station antennas utilizing MMSE detection.

Figure 6 presents a comparison of the three detection techniques for the same parameter configuration. It is clear that the MMSE performs the best in terms of BER, followed by the ZF and MRC. There is roughly a 3.8 dB SNR gain at BER = 10^{-4} between MRC and MMES, 3.1 dBs between MRC and ZF, and 1.6 dB between ZF and MMSE. The ZF receiver outperforms the MRC receiver because interference is the main factor impacting system performance at high SNRs and because it aims to eliminate interference. ZF ignores the impact of noise, therefore while it works well in low-interference environments, it is useless in noisy environments.

When it comes to M-MIMO systems, MRC is simple to implement, but it doesn't instantly eliminate interference. Additionally, there are no internal methods in MRC that can efficiently decrease inter-user interference. However, interference-aware algorithms like ZF and MMSE are both present. They aim to minimize or completely remove interference from other users by carefully adjusting the receiver weight. Given that MMSE and ZF are both interference-aware algorithms that employ CSI and optimal weighting to reduce inter-user interference, they typically exhibit closer BER performance in M-MIMO implementations. In addition, a key difficulty with M-MIMO systems is interference due to the multiple antennas and simultaneous transmissions. The MMSE receiver cancels or minimizes interference from other streams. ZF, which merely seeks to remove interference without taking noise into account, is less effective than MMSE in interference mitigation.

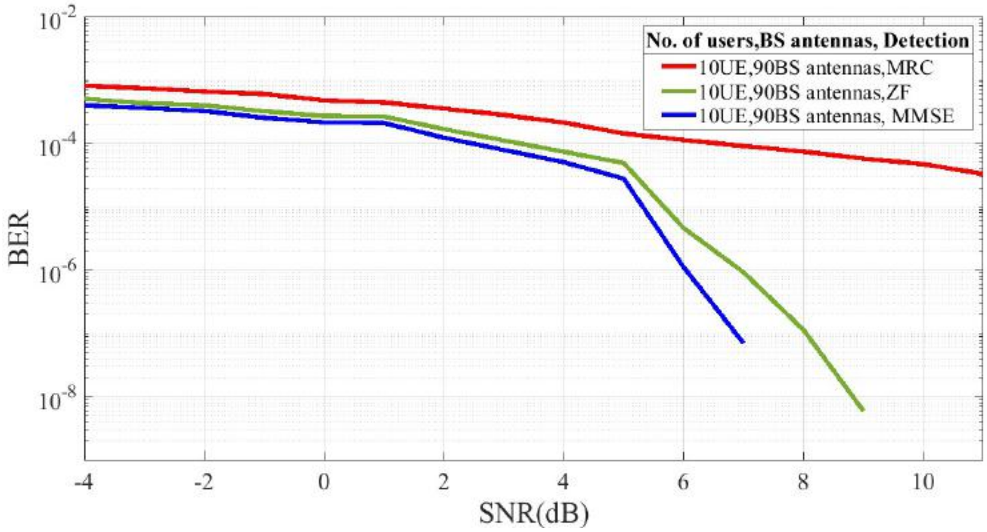

Figure 6: Comparison of the M-MIMO system's BER employing MMSE, ZF and MRC detections.

Figure 7 presents a final comparison of the three receivers for both coded and uncoded NR-LDPC situations. As shown in **Figure** 7, channel coding is a useful technique for improving M-MIMO reliability. Interference management is essential in M-MIMO systems because of the multiple antennas and simultaneous broadcasts they include. Because of their ability to repair errors, NR-LDPC codes can reduce interference and enhance BER performance.

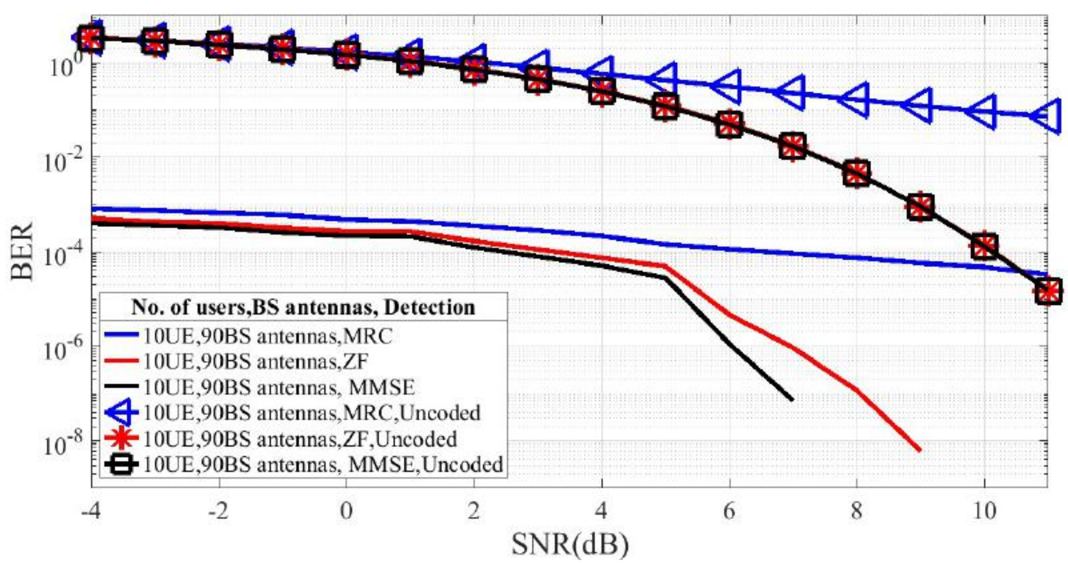

Figure 7: Comparison between the coded and uncoded M-MIMO system's BER using MRC, ZF and MMSE detections.

Conclusions

This paper provides a way to quantify the impact of channel coding on the BER performance of M-MIMO system. The approach that was provided centered on examining M-MIMO system and contrasting how well these systems performed when their design parameters were changed. The utilization of NR-LDPC codes in M-MIMO systems yields a noticeable enhancement in communication reliability and effectiveness, as it minimizes the errors caused by noise and channel variance.

The hundreds of serving antennas at the BS are one of the elements affecting the M-MIMO system's performance. The number of active users interacting with the BS concurrently and on the same frequency resources is another aspect that affects system performance. Another challenge that needs to be considered is choosing the type of equalizer that minimizes interference between the combined signals received from all active users.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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