Equalization Based Soft Output Data Detection for Massive MU-MIMO-OFDM Using Coordinate Descent

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Abstract. For the next generation of wireless communication networks to advance, massive multi-user multiple-input multiple-output orthogonal frequency division multiplexing (MU-MIMO-OFDM) systems are essential. Nevertheless, due to the concurrent presence of several users and the frequency-selective fading channel, identifying sent data in such systems proves to be a daunting issue. This study proposes a huge MU-MIMO-OFDM system-compatible coordinate descent-based equalization-based soft output data identification technique. This algorithm's major goals are to improve the estimation of transmitted data symbols and effectively deal with inter-user interference. By exploiting the sparse nature of the channel impulse response, the data detection problem as a joint sparse signal recovery and symbol detection task. Then, the coordinate descent algorithm, which iteratively updates the estimated symbols and exploits the sparsity structure of the channel has been implemented. These soft outputs can be utilized in subsequent stages of the communication system, such as channel decoding or interference cancellation. The simulation results clearly illustrate the superiority of the proposed method over existing detection techniques in terms of bit error rate (BER) performance. The algorithm showcases remarkable enhancements in detection accuracy, even in challenging scenarios involving a substantial number of users and severe channel conditions. When the number of base stations is increased from 32 to 128, the proposed algorithm demonstrates a substantial 76% reduction in bit error rate (BER). In contrast, conventional methods only achieve a value of approximately 60% reduction in BER under the same conditions.

Keywords: Accuracy · Interference · Equalization · Multiplexing · Soft-output data detection · Bit error rate

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P. Pareek et al. (Eds.): IC4S 2023, LNICST 537, pp. 173–184, 2024.
https://doi.org/10.1007/978-3-031-48891-7_14

1 Introduction

Massive Multiuser MIMO [1] (Multiple-Input Multiple-Output) with Orthogonal Frequency Division Multiplexing (OFDM) is a state-of-the-art technique that uses multiple antennas at the transmitter and receiver along with OFDM modulation to significantly increase the capacity and spectral efficiency of wireless communication systems [2]. It is considered a key technology for next-generation wireless networks, such as 5G and beyond. By employing multiple antennas [3–6], MIMO can exploit spatial diversity [7] and multiplex multiple data streams simultaneously, leading to increased data rates and improved reliability.

The modulation method (OFDM) divides the available frequency spectrum into several orthogonal subcarriers. These subcarriers can transmit data efficiently through frequency-selective channels at high data rates because they are individually modulated with low symbol rates. Modern wireless communication systems now use OFDM as a core component; it is widely used in Wi-Fi, LTE, and the most recent 5G networks. Massive multiuser MIMO OFDM combines the benefits of MIMO and OFDM to achieve high spectral efficiency and accommodate a large number of users simultaneously [8]. In this system, a base station or access point is equipped with a massive number of antennas, which can be in the hundreds or even thousands. These antennas are used to serve multiple users simultaneously by transmitting independent data streams to each user. At the receiver side, user devices are equipped with multiple antennas to receive the transmitted signals. The receiver uses advanced signal processing techniques, such as linear precoding and spatial multiplexing, to separate and decode the signals from different users [9]. The combination of massive antenna arrays, spatial processing, and OFDM enables Massive Multiuser MIMO OFDM systems to achieve high spectral efficiency, robustness against multipath fading, and improved interference management. It can support a large number of users with high data rates, making it suitable for dense urban environments and scenarios with high user demands [10].

With significant improvements in capacity, coverage, and user experience, the integration of these systems has the potential to completely alter wireless communication networks [11]. Future technological developments, like as smart cities, the Internet of Things (IoT), and improved mobile broadband applications, are expected to be made possible by this technology. Inspite of having numerous advantages, these systems are facing severe challenges in output data detection [12], resource allocation [13–15]. The factors which affect the output data detection includes: channel estimation; pilot contamination; interference; complexity; multiuser synchronization; imperfect channel knowledge [16]. Addressing these challenges requires advanced signal processing techniques, such as iterative detection and interference cancellation algorithms, efficient pilot designs, robust channel estimation algorithms, and adaptive modulation and coding schemes. Current research endeavors are dedicated to crafting efficient algorithms and system designs aimed at surmounting these challenges and elevating the performance of such systems.

2 Literature Review

Massive MU-MIMO-OFDM is indeed an important area of research with numerous future research directions. Some of the key areas where research is actively being pursued are: channel modeling; signal processing algorithms; interference management and resource allocation; hybrid beam forming and antenna design; spectrum efficiency and energy efficiency; cooperative and distributed massive MIMO; and practical implementation challenges. The authors of [17] has explored the potential improvement in throughput performance of a MU-MIMO system. In [18], the authors have introduced a novel precoding scheme called SB (Sum-Rate Maximizing Beam forming) that aims to maximize the total channel capacity.

To choose users in a multi-user communication system, the authors in [19] present an ideal pair-wise semi-orthogonal user selection (SUS) scheduling algorithm. The objective is to achieve higher throughput by effectively selecting users and optimizing sub channel allocation using these techniques. A novel MU-MIMO-OFDM scheme that employs spreading codes to achieve signal separation among mobile terminals has been presented [20]. The primary challenge in conventional multiuser MIMO systems is the presence of co-channel interference among mobile terminals. A new nonlinear distortion suppression method for MU-MIMO-OFDM systems is presented in this study [21]. A different study [22] focuses on creating MU-MIMO techniques that are specifically designed for OFDM systems, with an emphasis on those covered in the IEEE 802.11ac standard. In addition, a cutting-edge method [23] for guard interval (GI) control in MU-MIMO-OFDM systems for unmanned aerial vehicles (UAV) is described. Additionally, a set of waveforms for shaping the subcarriers in MU-MIMO-OFDM systems are proposed in this study using a computationally effective optimization method [24].

3 Methodology

3.1 System Model

In this scenario, a high-capacity uplink system utilizing massive MU-MIMO-OFDM technology has been analyzed [25]. The system comprises U user terminals, each equipped with a single antenna, which transmit data in parallel to a base station possessing BS antennas. The transmission takes place across W subcarriers, enabling efficient utilization of the available spectrum. In this setup, each user (indexed as $i = 1,\ldots, U$) employs a forward error-correction scheme to encode its own bit stream. The resulting coded bits are then mapped onto constellation points from a finite set, such as 64-QAM, utilizing a gray mapping rule. It is assumed that the average transmit power of each user is normalized to unity. Consequently, the obtained frequency-domain symbols on each of the W subcarriers are denoted as $\{s(i)_1,\ldots, s(i)\}$. Upon reaching the base station, the cyclic prefixes are removed, and the *TD* signals from each antenna undergo a DFT operation, converting them back into the *FD*. For this system, it is assumed that a sufficiently long cyclic prefix is available, ensuring ideal synchronization between users and the base station. Additionally, accurate knowledge of the channel state information

(CSI) is assumed [26], and the input and output for the w^{th} subcarrier can be commonly represented by Eq. (1) (Fig. 1).

$$y_w = H_w s_w + n_w \tag{1}$$

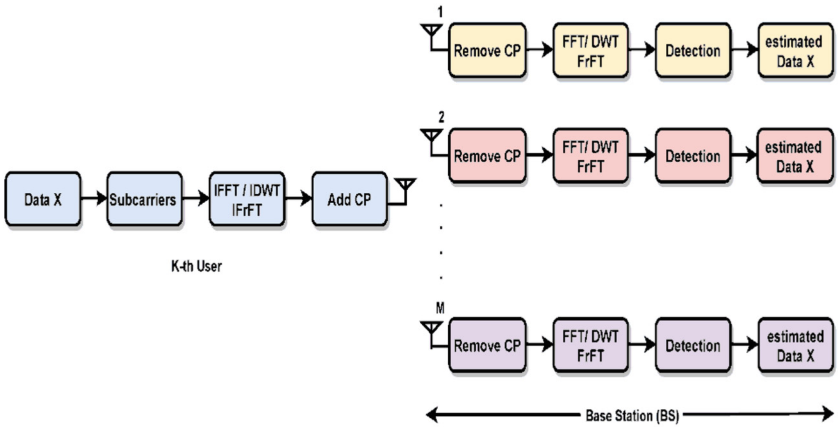

Fig. 1. Proposed uplink system model [25].

3.2 Data Recognition Based on Equalization

Zero-forcing Equalization. In the context of the described system, equalization-based data detection is employed to recover the transmitted symbols at the base station. One commonly used equalization method is known as zero-forcing (ZF) equalization [27]. ZF equalization can be represented using (2), which aims to eliminate the interference caused by the channel by inversely applying the estimated channel response to the received signals.

$$\hat{y}(i)_w = {}^{y(i)_w}/_{\hat{H}(i)_w} \tag{2}$$

Linear MMSE Equalization. In addition to zero-forcing (ZF) equalization, another commonly used equalization technique in the context of MU-MIMO-OFDM systems is linear MMSE equalization [28, 29]. By considering both the channel response and the noise, this equalization tries to reduce the mean square error between the equalized symbols and the actual transmitted symbols. Mathematically, this can be represented using (3). The MMSE weight vector $\hat{W}(i)$ can be computed using (4), where *R(i)* is the covariance matrix of the received signal.

$$\hat{y}(i)_w = \hat{W}(i) \times H(i)_w \times y(i)_w \tag{3}$$

$$\hat{w}(i) = R(i)^{-1} \times h(i) \tag{4}$$

Non-linear Box-Constrained (BOX) Equalization. It is an advanced equalization technique used in wireless communication systems, including MU-MIMO-OFDM systems. Unlike linear equalization methods such as zero-forcing (ZF) and linear MMSE, BOX equalization operates in the non-linear domain and incorporates additional constraints to improve the equalization performance. In BOX equalization, the goal is to minimize the symbol error rate by formulating an optimization problem subject to box constraints on the equalized symbols. These box constraints ensure that the equalized symbols fall within a predefined range or region, typically based on the characteristics of the modulation scheme. Mathematically, the BOX equalization problem can be formulated using (5).

$$minimize \sum \left|y(i)_w - \hat{y}(i)_w\right|^2 \ subject\ to\ I \le \hat{y}(i)_w \le u \tag{5}$$

Coordinate Descent. Equalization via coordinate descent is an optimization technique used to expedite the process of equalization in communication systems [30]. Specifically, it is applied in scenarios where equalization involves solving a complex optimization problem with multiple variables. In coordinate descent, the optimization problem is divided into sub problems, each involving only a single variable. The idea is to iteratively update each variable while keeping the others fixed, cycling through all the variables until convergence is achieved. This approach simplifies the optimization process and can significantly reduce the computational complexity compared to traditional optimization algorithms. Coordinate descent (CD) is a widely recognized iterative framework used for precisely or approximately solving numerous convex optimization problems. It achieves this by performing a sequence of straightforward updates on individual coordinates. The CD framework can be described by Eq. (6).

$$f(z_1, \ldots . z_U) = f(z) = \|y_w - H_w z\|^2 + g(z)$$

4 Simulation Parameters

To perform simulation, several parameters need to be considered. The following are some of the key parameters required for such a simulation: system configuration; channel model: modulation and coding; equalization and detection; simulation parameters etc. These parameters provide the foundation for setting up a simulation environment to investigate the performance of proposed system. The specific values chosen for these parameters will depend on the specific scenario, research objectives, and available resources. Table 1 contains a list of the proposed model's simulation requirements.

Table 1. Simulation parameters

Parameter	Description
BS Antenna	32, 64,128
Modulation Scheme	16-QAM
Users	8
Detector Structure	ZF, MMSE, SIMO, OCDBOX, OCDMMS
Length of Data	16
Length of Frame	128
Subcarriers	2048
Cyclic Prefix	10
SNR (dB)	0–30

5 Experimental Outcomes

For the purpose of assessing the OCD-BOX algorithm's performance in terms of error rate, a Monte Carlo simulation of a coded MIMO-OFDM uplink system has been carried out. The system operates with a bandwidth of 20 MHz and consists of 2048 subcarriers, where 1200 subcarriers are dedicated to data transmission, following the specifications of LTE Advanced (LTE-A). The simulation has been employed 64-QAM modulation with gray mapping, which allows for efficient mapping of coded bits onto constellation points have been utilized. To enhance the reliability of the transmission, a rate-3/4 turbo code for forward error correction. BER analysis has been done to assess how well the proposed system model performs while taking different base station antenna configurations and different OCD iterations (k) into account. It is observed from Fig. 2, that the BER has been improved as the base station configuration irrespective of equalization technique. The proposed OCD-BOX has attained similar BER performance with OCD MMSE at larger BS configurations.

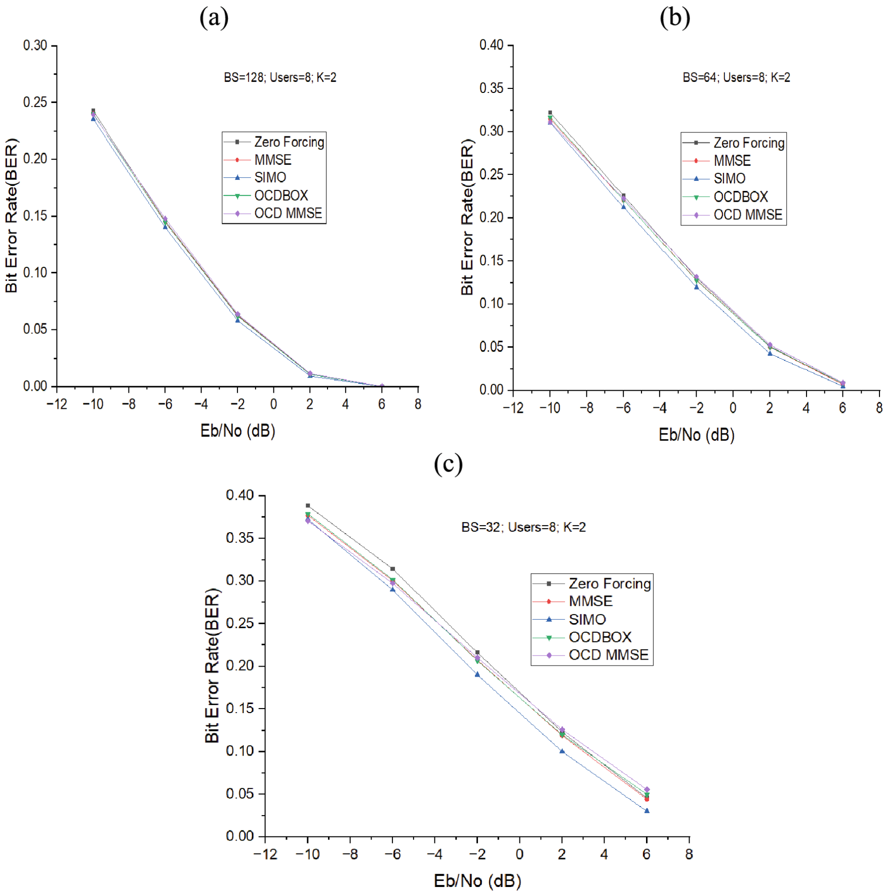

Fig. 2. BER for a massive MU-MIMO-OFDM system (k = 2, user = 8) with a) BS = 128 b) BS = 64 c) BS = 32

With only three simulation runs (K = 3), the suggested system achieves performance that is nearly identical to the ideal MMSE equalizer when used with 64 and 128 base station (BS) antennas (see Fig. 3). However, four iterations (K = 4) are necessary in the case of a comparatively smaller system with 32 BS antennas in order to attain comparable performance. Reduced performance is indicated by higher error floors caused by lower values of k (see Fig. 4). These simulation findings demonstrate that approximation linear data detectors can perform as well as the ideal MMSE detector in systems with a higher proportion of BS antennas to user antennas. An economical and effective solution for large-scale MU-MIMO systems is provided by the suggested system, which demonstrates an impressive capacity to approach MMSE performance with less iterations. In conclusion, in systems with 64 and 128 BS antennas, OCD-BOX achieves almost equal MMSE performance with only three rounds. However, four simulation runs are required in systems with 32 BS antennas to get comparable performance.

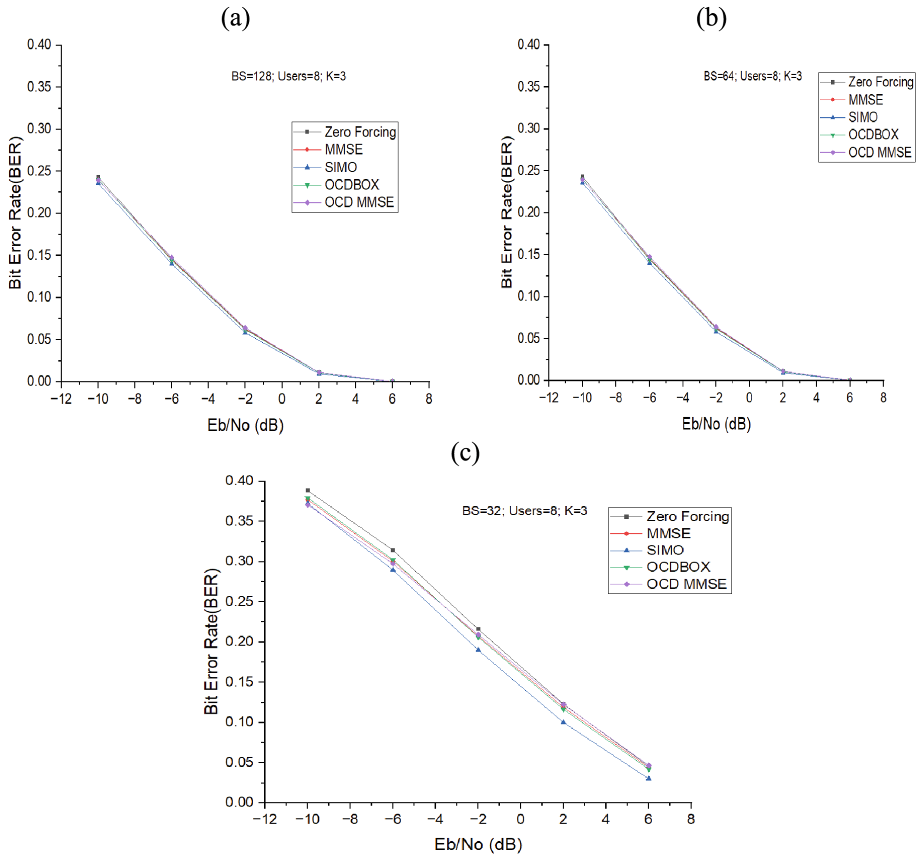

Fig. 3. BER for a massive MU-MIMO-OFDM system (k = 3, user = 8) with a) BS = 128 b) BS = 64 c) BS = 32

The comparison performance metrics for different equalizers by varying the value of *k* have been tabulated in Table 2.

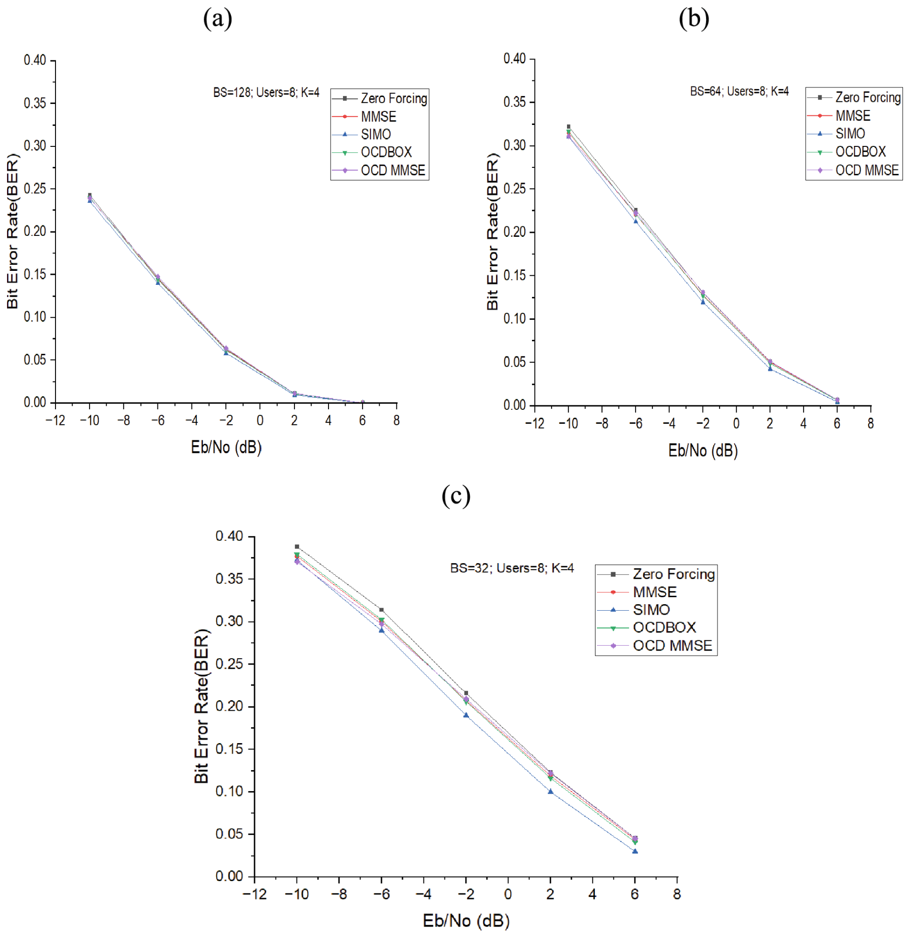

Fig. 4. BER for a massive MU-MIMO-OFDM system (k = 5, user = 8) with a) BS = 128 b) BS = 64 c) BS = 32

Table 2. BER Vs SNR for k = 2 (OCD iterations)

	BER (k = 2, BS = 128, Users = 8)				
SNR	ZF	MMSE	SIMO	OCDBOX	OCDMMSE
−10	0.24295	0.240166	0.235778	0.240234	0.239615625
−6	0.14600625	0.145072	0.140172	0.144613	0.148096875
−2	0.06295938	0.062538	0.058216	0.062106	0.06390625
2	0.011175	0.011047	0.009519	0.011034	0.011621875
6	0.00023438	0.000231	0.000156	0.000234	0.00026875
10	0	0	0	0	0

6 Conclusion

Despite this complexity challenge, researchers and engineers are actively working on developing efficient solutions to address the implementation complexity of massive MU-MIMO. Various algorithms and techniques, such as linear and non-linear equalization, soft output data detection, and optimization methods like coordinate descent, are being explored to reduce the computational burden at the BS while maintaining performance. This study proposes a huge MU-MIMO-OFDM system-compatible coordinate descent-based equalization-based soft output data identification technique. The simulation results clearly illustrate the superiority of the proposed method over existing detection techniques in terms of bit error rate (BER) performance. The algorithm showcases remarkable enhancements in detection accuracy, even in challenging scenarios involving a substantial number of users and severe channel conditions. When the number of base stations is increased from 32 to 128, the proposed algorithm demonstrates a substantial 76% reduction in bit error rate (BER). In contrast, conventional methods only achieve a value of approximately 60% reduction in BER under the same conditions.

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