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Optimizing multi-antenna M-MIMO DM communication systems with advanced linearization techniques for RF front-end nonlinearity compensation in a comprehensive design and performance evaluation study

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ABSTRACT

The study presented in this research focuses on linearization strategies for compensating for nonlinearity in RF front ends in multi-antenna M-MIMO OFDM communication systems. The study includes the design and evaluation of techniques such as analogue pre-distortion (APD), crest factor reduction (CFR), multi-antenna clipping noise cancellation (M-CNC), and multi-clipping noise cancellation (MCNC). Nonlinearities in RF front ends can cause signal distortion, leading to reduced system performance. To address this issue, various linearization methods have been proposed. This research examines the impact of antenna correlation on power amplifier efficiency and bit error rate (BER) of transmissions using these methods. Simulation studies conducted under high signal-to-noise ratio (SNR) regimes reveal that M-CNC and MCNC approaches offer significant improvement in BER performance and PA efficiency compared to other techniques. Additionally, the study explores the influence of clipping level and antenna correlation on the effectiveness of these methods. The findings suggest that appropriate linearization strategies should be selected based on factors such as the number of antennas, SNR, and clipping level of the system.

Keywords: Information Technology, Network, Multi-antenna communication, M-MIMO, OFDM system, Computer Science.

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1. Introduction

Wireless connectivity and the presence of cellular networks have profoundly influenced the global lifestyle and the way humans interact as mentioned in [1]. Having access to a broadband network full of services and entertainment deemed smartphones to become a basic good according to [2]. The rising demand for throughput and connectivity can be seen in the development trends of the previous and future generations of wireless networks according to [3,4]. Starting from the second generation of cellular networks (2G) the main effort was focused on providing greater throughput and efficiency to facilitate the use of Internet services on mobile devices. The demand for higher data rates and capacity in wireless networks seems insatiable according to [5]. The current deployment of the fifth generation of cellular networks (5G) is destined to meet the growing requirements, but only temporarily as research works have already begun on the next generation, which is the 6G as stated in [7]. According to Ericsson Mobility Report, [8,9] 5G mobile subscriptions are expected to surpass 1 billion in 2022 and by the end of 2027, their number should reach 4.4 billion. The report also observed that mobile network traffic has doubled in the last two years, a trend which is expected to continue in the coming years. Figure 1.1 presents the global trends regarding mobile data traffic. The Internet report by Cisco [10] and the mobility report by Ericsson [11], clearly highlight the need for continuous improvement in the domain of wireless technologies to meet the rising demands of modern, digital societies. It is worth presenting the technical milestones of 5G to give a sense of the scale of the challenge. Key features of the currently deployed 5G according to ITU-R [12]:

- User data rates of 100 Mbit/s and peak data rate of 20 Gbit/s
- 100x improved network energy efficiency, 10x prolonged battery life and 3x better spectrum efficiency regarding the previous generation
- Latency of 1ms and supported mobility of up to 500 km/h
- Area traffic capacity of 10 Mbit/s/m2 (1000x more compared to the previous generation)
- Up to 1 billion connected devices per square kilometer including the Internet of Things (IoT).

To support the objectives set for the 5G in presence of the limited radio resources, several novel technologies and approaches had to be introduced [13],[14]:

- Densification of cellular networks with a focus on heterogeneity and coexistence of multi-tier networks. Massive adaptation of small cells.
- Massive MIMO (M-MIMO) utilizing arrays equipped with tens of antennas and advanced signal processing technologies such as 3D-beamforming, space-time precoding or successive interference cancellation. The use of M-MIMO allows exploiting spatial diversity to facilitate Spatial Division Multiple Access (SDMA).
- Utilization of millimeter wave (mmW) frequencies for new communication bands. Previously unexploited frequency ranges above 24 GHz, are to be used in small cells to create high- throughput, short-range links that should efficiently offload the traffic from higher-tier cells.
- Cloud-Based Radio Access Network (CRAN), shifting the base-band processing to the servers at the edge and introducing joint processing mechanisms to reduce the delays and operational costs.
- Network Virtualization, decoupling the network infrastructure from the physical resources, allowing for better utilization of computational and hardware resources resulting in improved network performance. The network functions are also virtualized regardless of the vendor hardware, improving scalability and interoperability.
- Green communications based on energy harvesting or renewable resources. Employing energy- aware communication schemes like simultaneous wireless information and power transfer. Aiming to reduce the carbon footprint of the telecommunications industry.

From the listed key enablers of the 5G, Massive MIMO appears to be one of the most interesting. A high number of transmitting and receiving antennas provides additional degrees of freedom which can be exploited with signal processing to improve the efficiency and performance of wireless transmission systems according to [15]. Only in the last decade, M-MIMO systems have gained overwhelming interest from academia and industry. The gains stemming from the utilization of antenna arrays in the communications are dependent on the selected transmit (TX) and receive (RX) processing algorithms as mentioned in [16]. With Massive MIMO, the performance of the above-mentioned techniques can be leveraged even further due to the greater number of antennas. Figure 1 (a) presents an illustrative case of beam forming with M-MIMO array, which is shaping the radiation pattern in the direction where the receiving device is located. Figure 1(b) presents an illustration of the transmit diversity in M-MIMO system. The channels between the transmit antennas vary, which can be exploited to improve the robustness of the wireless link.

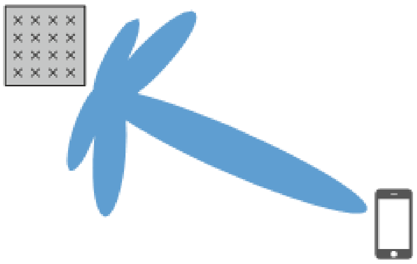

Figure 1(a): Beam forming in M-MIMO

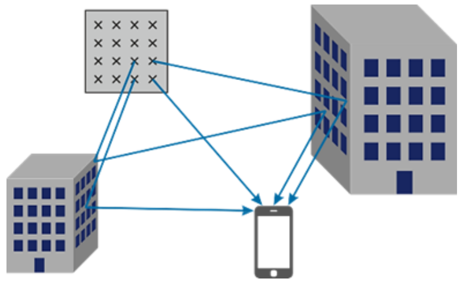

Figure 1(b): Transmit diversity in M-MIMO

Nonlinearity in the radio frequency (RF) front-end can reduce system performance in multi-antenna massive multiple-input multiple-output (M-MIMO) orthogonal frequency-division multiplexing (OFDM) communication systems by generating undesirable distortion and impairments. Techniques for linearization have been put forth to account for these impacts and enhance the performance of the system. The inter-antenna interference issue and high computing complexity of M-MIMO OFDM systems, however, may preclude the use of the present linearization approaches. Designing and evaluating new linearization approaches that are especially suited to handle the difficulties of nonlinearity compensation in M-MIMO OFDM communication systems is thus the key research subject in this study. Considerations for these approaches' performance evaluation should include inter-antenna interference, error rate, and computational complexity. To improve the performance of M-MIMO OFDM communication systems in the presence of RF front-end nonlinearity, a thorough examination of the effectiveness of the proposed linearization strategies is provided in this study.

The aim of this work is to study the influence of nonlinear distortion on a Massive MIMO system employing Orthogonal Frequency-Division Multiplexing (OFDM). The radiation characteristic of a M-MIMO array with front-end nonlinearity is analyzed both for wanted and distortion signals and its impact on the receiver performance is evaluated. Finally, two iterative distortion recovery algorithms are proposed and tested in the multi-antenna scenario and their gains are discussed.

- Perform a detailed study on the influence of front-end nonlinearity on Massive MIMO systems backed up by theoretical analysis and simulation results.
- Investigate the radiation characteristic of the desired and distortion signal components in a uniform linear array (ULA) and evaluate the Signal Distortion Ratio (SDR) for selected channel models.
- Evaluate the Bit Error Rate (BER) performance and the spectral characteristic of the received signals in the M-MIMO system in the presence of nonlinearity.
- Propose an iterative reception algorithm for reduction of nonlinear distortion and test its performance in a multi-antenna scenario. Propose a simplified algorithm to allow distortion cancellation with reduced computational complexity and reduced amount of control information.

2. **Literature review**

MIMO with multiple antennas Multiple methods is used in OFDM communication systems to improve system performance and reliability according to [17]. To improve spectral efficiency and decrease interference between antennas, precoders split the data stream into many parallel data streams. Interference, fading, and noise can all be reduced with the use of signal receiving techniques like channel estimation, equalization, and interference cancellation as mentioned in [18]. MIMO increases the system's dependability and spectral efficiency through the benefits of diversity and spatial multiplexing. With its high spectral efficiency, resistance to fading, and adaptability to diverse channel circumstances, OFDM is a prominent modulation technology used in multi-antenna M-MIMO systems according to [19]. Finally, CNC and MCNC are linearization techniques that cancel out clipping noise and quantization noise to correct for nonlinear distortion in the RF front-end. System complexity, power needs, and performance goals must all be considered throughout the design and performance evaluation of these methods as stated in [20]. Due to nonlinearity, the signal at the output of a PA contains unwanted signal components referred to as nonlinear distortion. The nonlinear distortion is manifested as harmonics at multiples of signal frequencies when the signal consists of discrete tones or as spectral regrowth when the input signal has a finite bandwidth as stated in [21]. The additional signal components are called intermodulation products. The presence of in-band distortion components degrades the performance of the system, while the out-of-band components may interfere with other wireless systems and similarly affect their performance. The influence of the nonlinearity on the signal can be characterized by the input signal Peak-to-Average Power Ratio (PAPR) [22]. The greater the PAPR the more significant the nonlinear distortion of the signal. High values of PAPR cause the input signal to drive the amplifier more into the saturation region resulting in a higher contribution of the nonlinear effects according to [23]. The linearization of RF front-end nonlinearity in communication systems has been the subject of extensive research. Digital predistortion (DPD), analogue predistortion (APD), and adaptive predistortion (ADP) are a few of the methods that have been suggested in the literature.

A multi-input multi-output (MIMO) DPD method was suggested in a paper [24] to address the nonlinearity in the RF front-end of a multi-carrier MIMO communication system. The performance of the system was shown to be greatly improved by the suggested DPD algorithm, which significantly reduced the nonlinearity distortion, when tested utilizing an orthogonal frequency-division multiplexing (OFDM) transmission system.

An APD method was suggested for reducing the RF front-end nonlinearity in a multi-antenna MIMO OFDM system in a subsequent work by Choi et al. (2017). The suggested method relied on injecting a predistorted signal into the RF front-end to balance out the nonlinear distortion that was brought on by the RF front-end. The bit error rate (BER) performance of the system was found to significantly improve with the proposed APD approach. An ADP approach was suggested in a paper [25] for reducing the RF front-end nonlinearity in a multi-antenna MIMO OFDM system. The suggested approach was based on adaptively adjusting the predistortion filter coefficients and estimating the nonlinear distortion using a pilot signal. A 4x4 MIMO OFDM transmission system was used to test the suggested ADP algorithm, and it was discovered to significantly increase system capacity and BER performance. So far, the M-MIMO OFDM receivers aware of nonlinear distortion have received limited attention in the literature. In [26] a neural network nonlinearity compensation for M-MIMO is presented, which can be applied both at the transmitter and receiver. The work addresses the problem by taking into consideration the distortion of the pilot signals providing channel state information. Another approach utilizing neural networks is presented in [27]. Note that neural networks require a relatively long training period to characterize the nonlinearity and effectively reduce the distortion. In [28] authors analyze the performance of derived linear mini- mum mean squared error-based receiver for M-MIMO and nonlinearity modeled as a third-order polynomial. The receiver offers an improvement in regard to BER, however, it is still far from reaching the performance of the system without nonlinear amplification. In [29] a joint channel equalization and iterative nonlinear distortion cancellation technique is discussed in Multi-User M-MIMO scenario. The utilized algorithm is very similar to the CNC, however it was not analyzed for any type of transmit precoding for the multi-antenna base station as shown in the Figure 2.

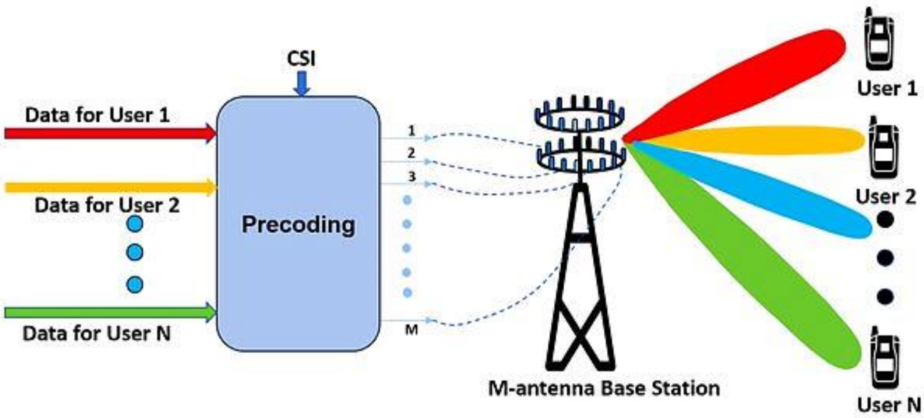

Figure 2. An architectural diagram to improve signal quality and lower interference, numerous antennas are employed at both the transmitter and reception ends of the system

Addressing the problem of nonlinear distortion at the transmitter, several PAPR reduction techniques have been proposed [30]. One commonly employed technique is Clipping and Filtering (CAF) presented in [31]. It allows for PAPR reduction without average power increase or band- width broadening. One critical issue of CAF is the presence of the in-band distortion originating from the clipping. In the literature two distinguished approaches toward distortion recovery, in single antenna systems, can be found: time-domain (TD) and frequency-domain (FD). The TD approach is represented by Decision-Aided Reconstruction (DAR) [32] and

FD approach by Clipping Noise Cancellation (CNC) [33]. In [34] it has been shown that the CNC algorithm outperforms the DAR which was supported by derivation of theoretical performance bounds. In [35] authors propose a novel precoding method for large arrays, in which the main feature is canceling the coherent combining of the third-order nonlinear distortion. The effort and focus on the problem of the nonlinear distortion points to a conclusion that it is still of major importance even in M-MIMO systems and measures must be taken to mitigate its effects on the system's performance. The study by [36] proposes a condition-based maintenance assisted learning approach to address the challenges of evolving patterns of device failures over time and imbalanced data in smart manufacturing industries. The approach achieves a high level of accuracy in identifying minority instances, surpassing 96%. The goal of future wireless networks is to offer seamless connectivity between different communication networks, with various bandwidth and quality of service options available at any time and location. Media independent handover (MIH) is a successful deployment method for integrating heterogeneous wireless networks, which can provide information about the parameters that affect event generation. An effective system for generating links trigger mechanism will greatly impact handover performance [37-40].

3. **Methodology**

The study presents a systematic approach to designing the effectiveness of several linearization strategies for compensating for nonlinearities in the RF front end of M-MIMO OFDM communication systems with multiple antennas. The study created a simulation systematic model that considers all the potential system impairments and linearization approaches.

3.1 Design of system model

A transmission system depicted in Fig. 3 is considered. There is NU QAM symbols *sn* (n ∈ {1, ..., NU} transmitted over adjacent subcarriers in a single OFDM symbol period. The modulation symbols are chosen from set χ. The symbols are precoded and transmitted by *K* parallel transmitting signal chains, each consisting of an OFDM modulator with a maximum number of N subcarriers, a nonlinear amplifier, and an antenna element. Signals from different antennas combine at the single antenna receiver. The next subsections describe the signal processing in each of the functional blocks.

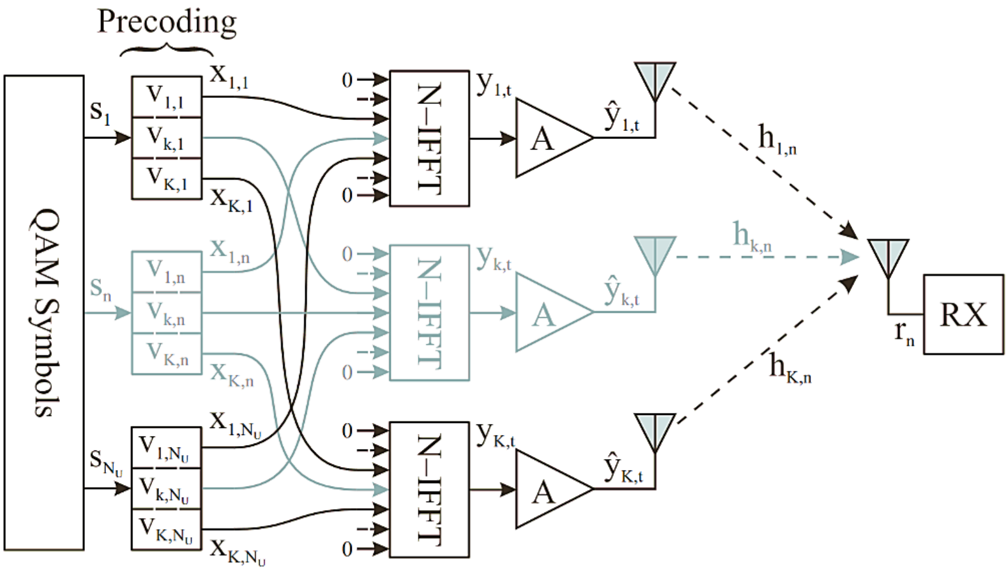

Figure 2. Functional design of the system model for the study of signal processing

To utilize the OFDM modulator, it is assumed that the radio channel is constant for the frequency span of a single subcarrier, i.e., channel coherence bandwidth is not smaller than a single subcarrier bandwidth. For n^{-th} subcarrier and k^{-th} antenna, the channel response is a single complex coefficient expressed as $h_{k,n}$.

Considered antenna channel types:

- Line-of-Sight (LOS): modelled as attenuation of the free space and phase rotation resulting from the distance between the transmitter and receiver.

- Two-path: apart from the direct path it includes an additional one corresponding to the reflection from the ground with a reflection coefficient equal to −1. The point of reflection is calculated taking into consideration the location of the RX and TX elements.
- Rayleigh: modelled as independent, identically distributed complex Gaussian variables for each subcarrier, antenna, and azimuth.

The key parameters of the considered M-MIMO system are shared within all analyses and simulation scenarios. The transmitting end was a uniform linear array with an inter-element spacing of half wavelength. Each antenna was modeled as an omnidirectional radiator with a gain of *0 dBi*. The transmitter end was positioned 15 m above ground level. Tab. 1 presents the details concerning the transmission system. Each front-end amplifier was modeled as a soft limiter with an identical cutoff power. A single receiver was placed 300 m from the TX at an azimuth of 45° and 1.5m above the ground level. The perfect Channel State Information (CSI) known both at the transmitter and receiver is assumed. The antenna array transmitters employ MRT precoding.

Table 1. Transmission system parameters

Parameter	**Symbol**	**Value**	**Unit**
Subcarrier spacing	Δf	15	[kHz]
Carrier frequency	f_c	3.5	[GHz]
Total number of subcarriers	N	4096	[−]
Number of data subcarriers	N_U	2048	[−]
QAM constellation size	M	64	[−]

Division of transmission system elements and functional blocks into classes allowed for simplification of the simulation scripts and provided much-needed scalability. The arrangement of antenna elements can be seen in Fig. 4 where the azimuth angle is denoted as θ.

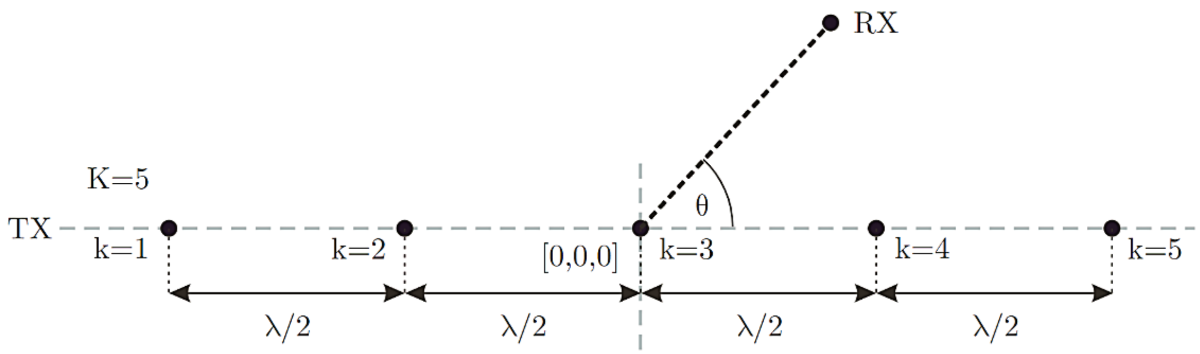

Figure 4. Antenna array arrangement with azimuth angle denoted as θ

3.2 Precoding for antenna communication

Precoding is applied by multiplying the data symbol at n-th subcarrier sn by precoding coefficient *vk,n* for n^th subcarrier and k^th antenna obtaining the precoded symbol xk,n:

$$\hat{y}_{k,t} = \alpha_k y_{k,t} + \bar{d}_{k,t}$$

It is assumed that the precoder is normalized to obtain a unitary summarized transmit power, gain, irrespective of the number of utilized antennas for each subcarrier independently:

$$\mathbb{E}\left[\left|y_{k,t}\right|^2\right] = \frac{\bar{P}_S}{NK}\sum_{n\epsilon E}\sum_{K=1}^{K}\left|v_{k,n}\right|^2 = \frac{\bar{P}_S N_u}{NK}$$

For a special case of maximum ratio transmission (MRT), which maximizes the received power, the precoding coefficients are calculated as eq. 3.

$$v_{k,n} = \frac{h_{k,n}^*}{\sqrt{\sum_{\bar{k}=1}^{k}\left|h_{\bar{k},n}\right|^2}}$$

3.3 OFDM modulation for multi-antenna communication

Precoded symbols are then subject to OFDM modulation, which is performed by Inverse Fast Fourier Transform (IFFT) of size N. Only Nu subcarriers of indices N are modulated by data symbols *xk,n*. The other N − NU subcarriers are modulated with zeros. Typically, for a sym- metric OFDM spectrum and an unused DC subcarrier the subcarrier indices set equals N = *{−Nu/2, ..., −1, 1, ..., Nu/2}*. The output of the IFFT t-th sample of OFDM signal for kth antenna is calculated as:

$$y_{k,t} = \frac{1}{\sqrt{N}} \sum_{n \epsilon N} x_{k.n} e^{j2\pi \frac{n}{N} t}$$

where t ∈ {−NCP, , N − 1}, and NCP is the number of samples of the cyclic prefix (CP).

The modulated signal is processed by a nonlinear amplifier model identical for each transmitting signal chain:

$$\hat{y}_{k,t} = A\big(y_{k,t)}\big)$$

which in the case of the soft limiter can be described as:

$$\hat{y}_{k,t} = \begin{Bmatrix} y_{k,t} & for\left|y_{k,t}\right|^2 \le P_{max} \\ \sqrt{P_{max}} e^{jarg(y_{k,t})} & for\left|y_{k,t}\right|^2 > P_{max} \end{Bmatrix}$$

where P_{max} is the maximum transmit power of a given Power Amplifier (PA) and arg (yk,t) denotes phase of $y_{k,t}$. If exceeded, the signal is clipped, i.e., has constant amplitude while maintaining the input phase. While there is several different PA models, the soft limiter is proved to be the nonlinearity maximizing the signal-to-distortion ratio. While in many contemporary systems digital pre-distortion is employed, the soft limiter can be treated as an optimal characteristic of the combined PA and pre-distorter model.

It is a common practice to use Input Back-off (IBO) parameter to determine PA operating point and respectively the P_{max}. It is defined as a ratio of maximum PA power to the average power at the input of the amplifier, expressed in decibels scale:

$$IBO[dB] = 10log_{10}(\frac{P_{max}}{\mathbb{E}\left[\left|y_{k,t}\right|^2\right]})$$

where the expectation operator is denoted as E.

Assuming that the average signal power is calculated based on an individual OFDM symbol samples over all antennas:

$$\mathbb{E}\left[\left|y_{k,t}\right|^2\right] = \frac{\bar{P}_S}{NK} \sum_{n \epsilon E} \sum_{K=1}^{K} \left|v_{k,n}\right|^2 = \frac{\bar{P}_S N_u}{NK}$$

where Ps is the average power of a single symbol s_n. If the wireless channel is varying in time the expectation over |vk,n|2 should be also considered. Because of averaging mean power over antennas in all *K* amplifiers work with the same clipping threshold P_{max}.

The signal at the output of the amplifier can be decomposed based on the principle of homogenous linear mean square estimation [28] as:

$$\hat{y}_{k,t} = \alpha_k y_{k,t} + \bar{d}_{k,t}$$

where αk is the correlation coefficient specific for kth antenna, *dk,t* is the distortion signal uncorrelated with the desired signal *yk,t*.

3.4 Signal reception

The Signal-to-Noise Ratio (SNR) is defined considering only the data-carrying subcarriers with the wanted signal attenuated by coefficients αk giving:

$$SNR = \frac{\bar{P}_S \frac{1}{N_U} \sum_{n \epsilon N} \left|\sum_{k=1}^{K} \alpha_k h_{k.n} v_{k.n}\right|^2}{\mathbb{E}[|w_n|^2]}$$

Based on the SNR definition the Eb/N0 can be calculated as:

$$\frac{Eb}{N0} = \frac{SNR}{log_2 M}$$

where *M* is the size of the constellation.

Similarly, the Signal-to-Distortion Ratio (SDR) is defined considering only the data-carrying subcarriers:

$$SDR = \frac{\bar{P}_S \sum_{n\epsilon N} \left|\sum_{k=1}^{K} \alpha_k h_{k.n} v_{k.n}\right|^2}{\sum_{n\epsilon N} \left|\sum_{k=1}^{K} h_{k.n} d_{k.n}\right|^2}$$

3.5 Clipping noise cancellation algorithm (CNC) & multi-antenna clipping noise cancellation (MCNC)

Clipping Noise Cancellation (CNC) receiver: Number of additions/subtractions:

$$3N_U + 3\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N_U M$$

$$\frac{5N_U + 5\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N log_2 N + 3N_U M}{0 - th\ iteration}$$

$$+I(2\left(5\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N log_2 N\right) + 70N + 2N_U + 3N_U M)$$

Number of multiplications/divisions in n-antennas:

$$\frac{3N_U + 3\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N_U M}{0 - th\ iteration}$$

$$+I(2\left(3\left(\left(\frac{N}{2}\right) log_2 N\right)\right) + 5N + 2N_U + 2N_U M)$$

Multi-antenna Clipping Noise Cancellation (MCNC) receiver:
Number of additions/subtractions:

$$2$$

$$\frac{5N_U + 5\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N log_2 N + 3N_U M}{0 - th\ iteration}$$

$$+I(K+1)\left(5\left(\left(\frac{N}{2}\right) log_2 N\right)\right) + 2N log_2 N) + 70KN + (2K+1)5N_U) + (K+1) + 2N_U + 3N_U M)$$

Number of multiplications/divisions:

$$\frac{3N_U + 3\left(\left(\frac{N}{2}\right) log_2 N\right) + 2N_U M}{0 - th\ iteration}$$

$$+I(K+1)\left(3\left(\left(\frac{N}{2}\right) log_2 N\right)\right) + 5KN + (2K+1)3N_U + 2N_U M)$$

TABLe 2. Number of operations of selected signal processing steps

Signal processing step	Operation count	
	Additions/Subtractions	Multiplications/Divisions
OFDM symbol detection	$3N_U M$	$2N_U M$
FFT/IFFT	$5\,((N/2)\log_2 N) + 2N\log_2 N$	$3\,((N/2)\log_2 N)$
Equalization	$5N_U$	$3N_U$
MIMO Precoding	$5N_U$	$3N_U$
MIMO Propagation	$5N_U$	$3N_U$
MIMO Nonlinearity	$70N$	$5N$

4. Results

To evaluate the performance M-MIMO system in the presence of the front-end nonlinearity a simulation framework was implemented. The framework was implemented using Python programming language based on the object-oriented programming paradigm. Division of transmission system elements and functional blocks into classes allowed for simplification of the simulation scripts and provided much-needed scalability. Where possible signal processing operations were performed with the use of matrices, Numpy library and Numba a high-performance Python compiler to speed up the computations.

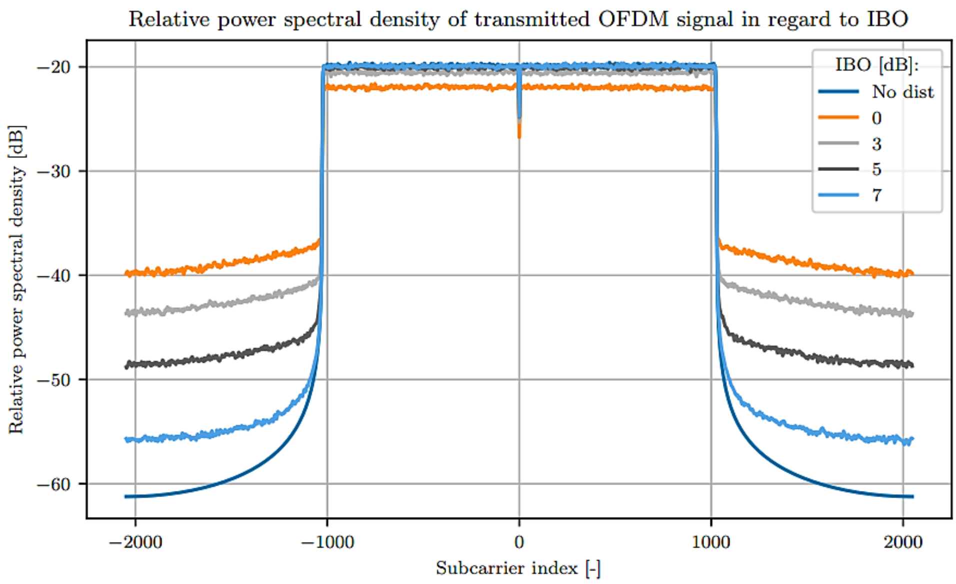

Figure 5. Relative power spectral density of the transmitted OFDM signal for selected IBO values

To gain insight into the properties of the transmitted signal Power Spectral Sensity (PSD) an analysis for MIMO system was first performed. For an uncoded single antenna system 100 OFDM frames were transmitted and collected to calculate the PSD at the output of the amplifier model. The model of nonlinear distortion was the soft limiter and the measurement was performed for a few values of the IBO.

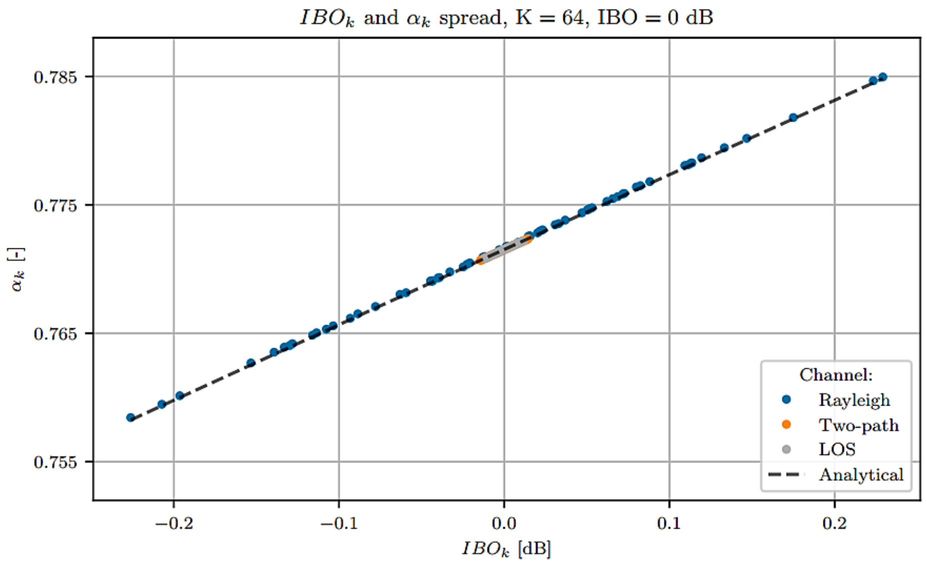

Figure 6. *IBOk* and *αk* values of individual antenna front-ends for K = 64, IBO = 0 dB, MRT precoding at azimuth angle of 45° and selected channels

The overall radiation pattern of the array varies in regard to the gain and number of side lobes with the number of antennas. Figure 7 presents the measure of the normalized radiation pattern of the distortion signal for a range of 16-128 antennas. It is visible that the more antennas are used the narrower beam can be generated and a higher number of sidelobes is present. Most importantly, while the radiation patterns of the desired signal are not shown, these have identical shapes as these ones for distortion signals shifted appropriately considering a constant signal-to-distortion ratio.

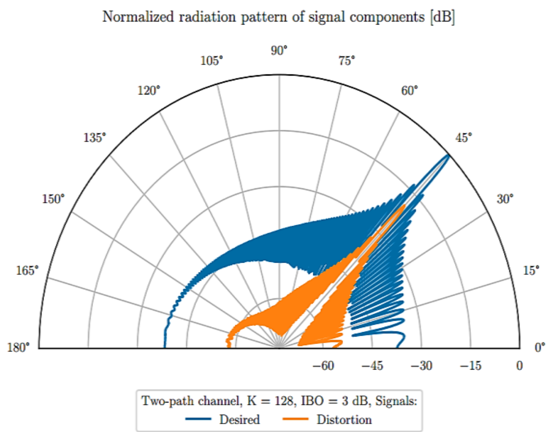

Figure 7(a). Normalized radiation pattern of desired and distortion signal components regarding azimuth angle for two-path channel model, 128 antennas and IBO = 3 dB

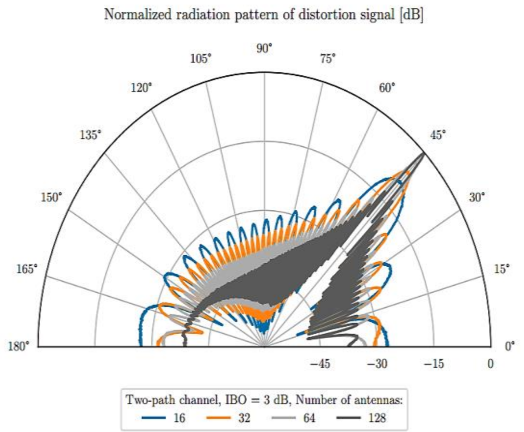

Figure 7(b). Normalized radiation pattern of distortion signal regarding azimuth angle for two-path channel model, IBO = 3 dB and selected numbers of antennas

Next, the Signal to Distortion Ratio (SDR) analysis was performed for all three considered channels: LOS, two-path and rayleigh and the selected number of antennas. Recall that SDR is calculated taking into consideration only the used subcarriers NU. The results for all considered channels are shown in Fig. 8. The results for the LOS channel agree with the earlier analyzes discussed in the literature review according to which the desired and distorted signal components are directed in the same way, resulting in a constant signal-to-distortion ratio regardless of the Signal to distortion ratio regarding channel and number of antennas and the azimuth angle used in the precoding.

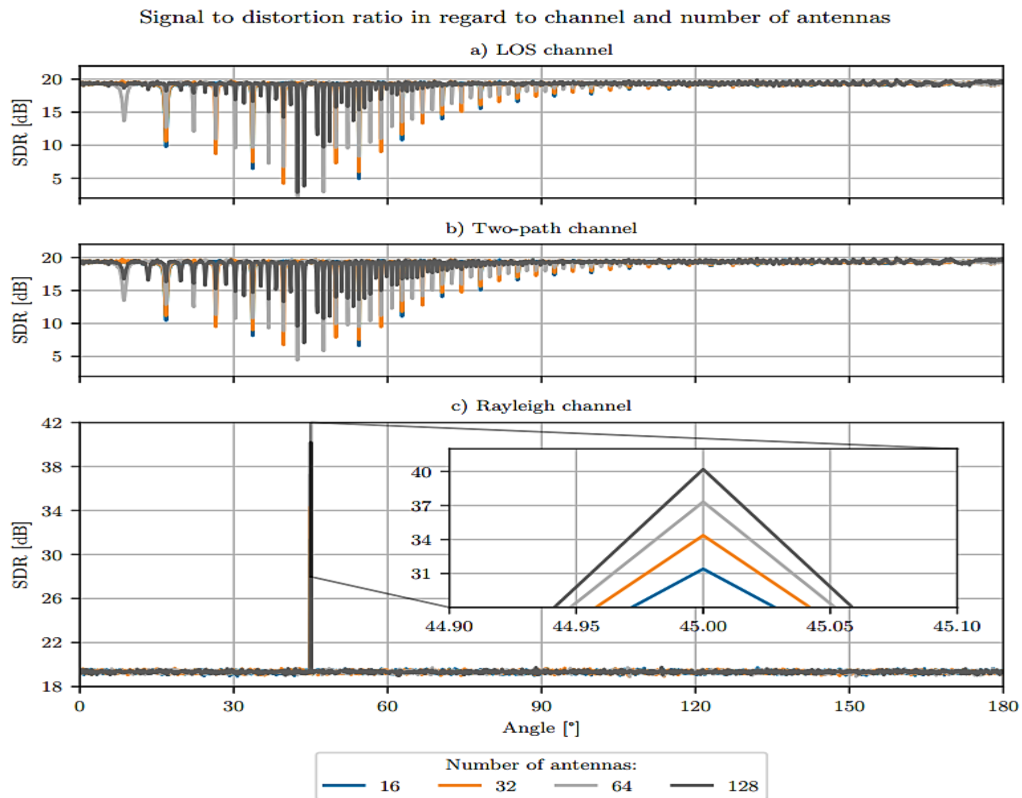

Figure 8. Signal to distortion ratio regarding angle and number of antennas for selected propagation channels and IBO = 3 dB

The SDR at user angles for multi-user precoding is higher by 3 dB compared to single-user cases. This result confirms that with a greater number of users the nonlinear distortion is far less harmful to the M-MIMO system and at some point, can be approximated as omnidirectional radiation. This allows us to emphasize that single-user precoding, further considered, is indeed the worst-case scenario from the receiver perspective in M-MIMO system.

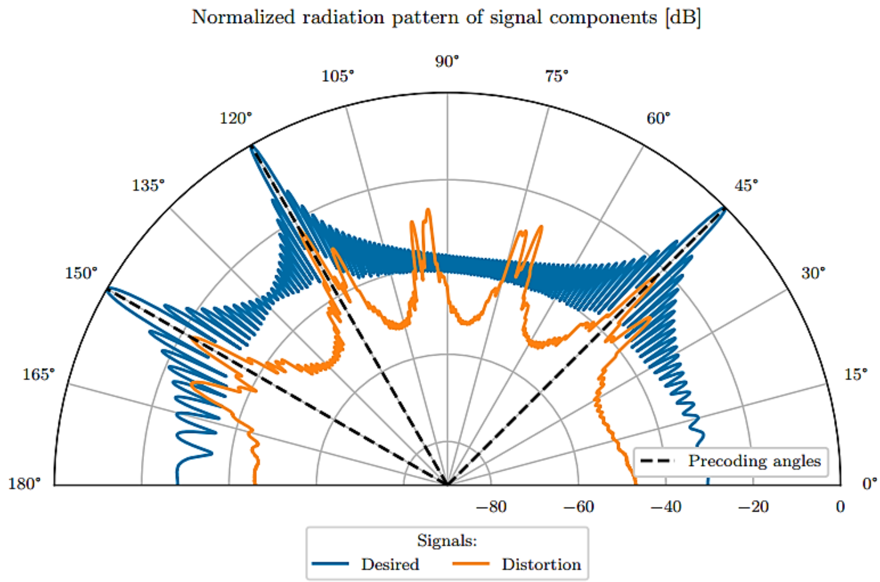

Figure 9. Normalized radiation pattern of signal components regarding azimuth angle for multi-user precoding, two-path channel model, IBO = 3 dB and 128 antennas

Figure 10 presents a comparison between CNC and MCNC algorithms taking into consideration the channel kind, number of RX iterations, and number of antennas K. The first observation can be a significant decrease of BER for the Rayleigh channel with several antennas. This effect is caused by averaging the channel resulting in higher signal power at the receiver and lower noise amplification during equalization. As expected from previous results, while the MCNC helps to improve the BER performance, the CNC algorithm increases BER in this scenario. For a high number of antennas in the Rayleigh channel, the SDR gains allow the MCNC algorithm to quickly converge within a single iteration to the noise-limited bound denoted as No dist. On the other hand, the CNC algorithm works well for LOS and two-path channels achieving BER slightly higher than the MCNC algorithm. Again, the performance of LOS and two-path channels is nearly identical. An interesting observation for these channels is that while the BER performance for both RX algorithms remains constant up to about K=16 antennas it starts to slightly decrease for higher K and higher number of RX iterations.

TABLe 3. Total number of operations for M = 64, N = 4096, NU = 2048, K = 64, and a selected number of iterations of the CNC and MCNC algorithms

Number of iterations: I	Total number of operations (10^6)			
	Additions/subtractions		Multiplications/divisions	
	CNC	MCNC	CNC	MCNC
0	0.62	0.62	0.34	0.34
1	1.75	35.07	0.78	7.50
2	2.88	69.52	1.21	14.66
3	4.00	103.96	1.64	21.82
4	5.13	138.41	2.08	28.97
5	6.26	172.85	2.51	36.13
6	7.38	207.30	2.95	43.29
7	8.51	241.74	3.38	50.45
8	9.64	276.19	3.82	57.60

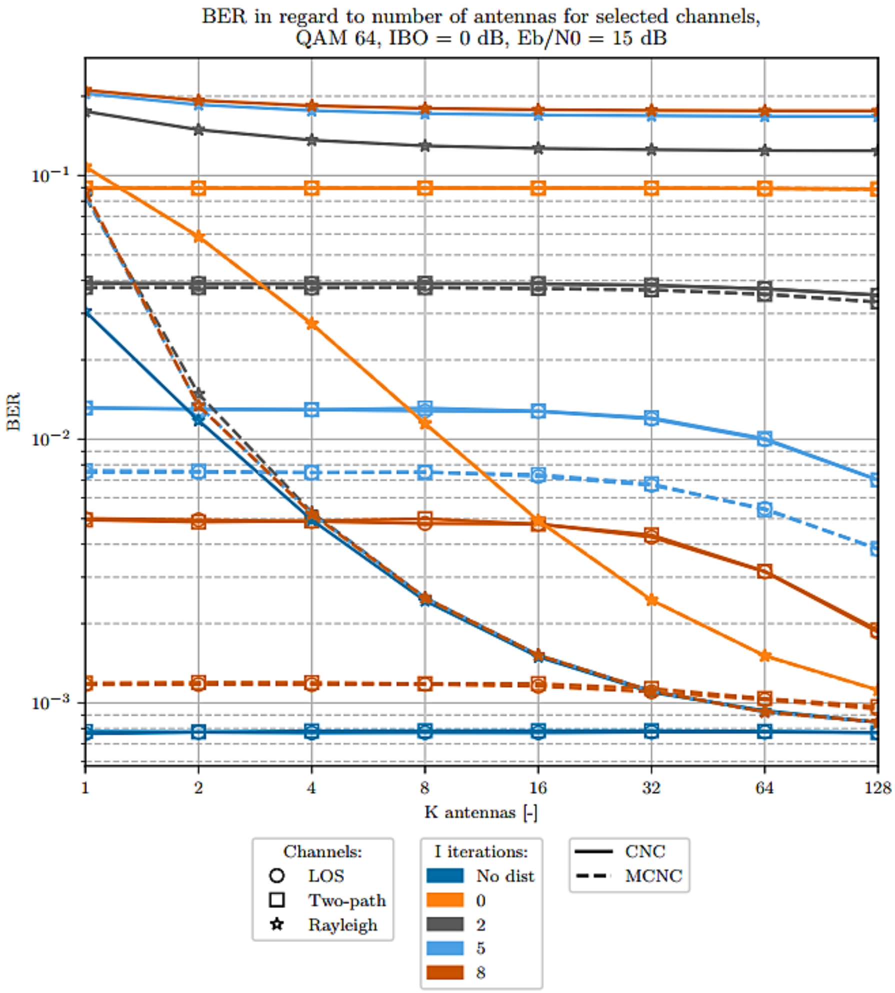

Figure 10. BER regarding the number of antennas, and channels for Eb/N0 = 15 dB, IBO = 0 dB, and a selected number of iterations of the CNC and MCNC algorithms

5. Conclusion

In this work, the influence of nonlinear distortion on the M-MIMO system has been studied. A mathematical model of the system was presented taking into consideration precoding and front- end nonlinearity. The simulation results provided insight into the radiation patterns of wanted and distortion signal components in the M-MIMO scenario. Moreover, the SDR was analyzed for a LOS, two-path and Rayleigh channels and a selected number of antennas. The analysis allowed to observe that in direct visibility channels the increase in the number of antennas does not improve the SDR and nonlinear distortion is still a major concern as it is beam formed in the same direction as the desired signal. While it was observed that nonlinear distortion can result in significant M-MIMO performance degradation, a Multi-antenna Clipping Noise Cancellation algorithm was proposed, to combat the problem at the receiver. The starting point for its design was CNC algorithm intended for MIMO systems. While MCNC is complex and computationally demanding a simplified version was proposed a MCNC for flat fading channels. Finally, by means of extensive simulation, the performance of CNC and MCNC algorithms have been compared and evaluated regarding several parameters. The proposed simplified algorithm proved to perform well for LOS and two-path channels with only slight degradation regarding MCNC, which may leverage its implementation in the M-MIMO OFDM receivers.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

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