Performance Analysis of Code-Domain NOMA in 5G Communication Systems

Conference Paper · January 2019

3 authors, including:

Zeyad Elsaraf
University of Huddersfield

Qasim Ahmed
University of Huddersfield

Performance Analysis of Code-Domain NOMA in 5G Communication Systems

Zeyad Elsaraf, Faheem Khan, and Qasim Ahmed
Department of Engineering and Technology
University of Huddersfield
Huddersfield, HD1 3DH, UK
zeyad.elsaraf@hud.ac.uk

***Abstract*—Today's wireless communication networks transmit their signals based on the Orthogonal Multiple Access (OMA) principle. As the number of users increases, OMA based approaches may fail to meet the stringent requirements emerging in the 5th Generation of wireless communications for very high spectral efficiency and massive connectivity. Non-Orthogonal Multiple Access (NOMA) emerges as a solution to improve upon spectral efficiency and user capacity without sacrificing system performance. This paper aims to demonstrate the validity of NOMA as an optimal choice for 5G by comparing it with OMA. Three Code-Domain NOMA (CD-NOMA) schemes are examined and compared with an established OMA technique, Orthogonal Frequency Division Multiplexing (OFDM). The chosen schemes for CD-NOMA are: Low Density Spreading CDMA (LDS-CDMA), Low Density Spreading OFDM (LDS-OFDM), and Sparse Coding Multiple Access (SCMA). The performance of each scheme is evaluated by computing its Bit error rate (BER) and Outage Probability (OP) and simulating them against different values of Signal-to-Noise-Ratio (SNR) over an AWGN channel. It is observed in this paper that, while having varying performance levels, every NOMA scheme outperforms OFDM, thereby proving NOMA to be a prime candidate for implementation in future 5G communication technologies.**

***Index Terms*—5G, orthogonal multiple access, non-orthogonal multiple access, code domain NOMA, spectral efficiency**

I. Introduction

As wireless connectivity spreads across the globe, a challenge for communication systems to accommodate the incoming wave of new users with limited available resources presents itself. To address this issue, novel communication techniques that allow for multiple users to access the same bandwidth have been developed for the fifth generation of mobile communications (5G). The currently utilized Multiple Access (MA) technique, Orthogonal Frequency Division Multiplexing (OFDM), may no longer satisfy the requirements of 5G since it relies heavily on allotting different frequency bands to users and stacking them orthogonally, which limits a system's user capacity by its bandwidth. Non-orthogonal multiple access (NOMA), however, explores a different approach in regards to increasing the user capacity and spectral efficiency of a system by allowing a number of users to occupy the same frequency band with little inter-user interference (ISI) [1]. NOMA techniques can be roughly categorized into two main classes: Power Domain (PD-NOMA), and Code Domain (CD-NOMA).

PD-NOMA explores a new dimension to be exploited for increasing user capacity where the available transmitting power at the base station is divided up between the users. A user's power allocation factor is determined via Channel State Information (CSI). That is, users with low CSI are assigned more power relative to users with higher CSI. Segmenting the available power levels in this manner allows a system to promptly serve users with poor channel conditions or users located at the cell edge as opposed to OMA, where users with higher CSI are favoured and users with poor channel conditions have to wait for access according to the time slot assigned to them. At the transmitter side, users are allocated different power levels and their signals are then superposed and sent through to each user in the system. The difference in power between each user is used to perform Successive Interference Cancellation (SIC) at the receiver side [2]. Signals with higher power levels are subtracted from the received signal, leaving only that user's low power signal. It is entirely possible to achieve Multiple User Detection (MUD) for an increasing number of users occupying the same frequency subcarrier with more sophisticated SIC methods, although this requires additional processing power at the receiver(s). [3]-[4]

In conventional CDMA, users can share a common channel simultaneously. User separation is done by assigning codes, or spreading signatures, to each user uniquely. However, as a result of this channel sharing, ISI in CDMA-based systems is unavoidable. CD-NOMA mitigates this limitation by utilizing spreading codes with low density signatures (LDS) and interleave sequences. In CD-NOMA, signals are spread using LDS (LDS-CDMA) which are comprised of sparse spreading codes each containing a small number of non-zero elements. The sparsity of the codes allows for the generation of more unique codewords for signal transmission which, in turn, allows for more users to be non-orthogonally superimposed on a chip. Unlike PD-NOMA, by utilizing Message Passing Algorithms (MPA), discussed in [5], user separation at the receiver can be carried out even when the received users' power levels are comparable. Another advantage of LDS-CDMA is its ability to achieve overloading, that is when the number of users in a system exceeds the processing gain. While the number of users in an overloaded system requires reduced sparsity of spreading codewords, it was proven in [6] that the number of spreading codes can be increased by up to 300% in a noiseless environment. Overloaded spreading codes are generated in accordance to the Welch Bound Equality [7] in order to reduce ISI.

The LDS-OFDM system can be understood as a system which utilises LDS for multiple access and OFDM for multicarrier modulation mapping. Due to its orthogonal mapping and sparse spreading, LDS-OFDM benefits from frequency diversity as well being able to achieve overloading. This allows a system's user capacity to rise as well as reduce the ISI that would usually accompany it. However, this convenience comes at the price of high, sometimes unaffordable, receiver complexity. [8]

SCMA further optimizes the sparse spreading in LDS-CDMA by combining the LDS spreader with QAM mapping to directly map a set of bits to a complex sparse vector to generate codewords [9]. SCMA codewords are sparse and allow for overloading much like LDS. Codebooks containing multidimensionally mapped codewords replace modulation mapping and spreading, allowing SCMA to benefit from multidimensional and shaping gains as opposed to code repetition in LDS. These gains are offset by a complex design procedure for SCMA codebooks as each multidimensional layer is designed using Euclidean geometry. However, SCMA enjoys a moderate receiver complexity since the codebooks are transparent between the transmitter and receiver. This paper is organised as follows: Section II presents the NOMA techniques' system models. Section III uses the bit error rate and outage probability to evaluate each scheme's performance when transmitting over an AWGN channel (OFDM is used as a base for comparison). Finally, Section IV concludes the paper's findings and suggests further future directions for NOMA research.

II. System Model

A. LDS-CDMA

Consider a CDMA system with K users. Let $y, \mathbf{H}, x, \mathbf{v}$ denote the superposed transmitted signal, effective received signature, transmitted symbols, and noise vectors respectively. As shown in Fig.1, the LDS spreading in this paper is divided into three stages: Spreading, Zero-padding, and Interleaving. Spreading is done with a randomly generated Hadamard matrix, where the k^{th} user is spread with the codewords in the n^{th} row. Zero-padding and Interleaving are designed to further increase the sparsity of the spread codeword(s) while maintaining the processing gain. The transmitted signal can be represented as

$$\mathbf{y} = \sum_{k=1}^{K} \mathbf{h}_k x_k + \mathbf{v} \tag{1}$$

which can be further generalised as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{v} \tag{2}$$

The effective received signature can be denoted as

$$\mathbf{H} = \mathbf{AGS} \tag{3}$$

where $\mathbf{A}$, $\mathbf{G}$, and $\mathbf{S}$ represent the users transmit gain, the corresponding channel gain, and the spreading signature of each user. From (1) and (2), an expression for the received signal of each user can be written as

$$y_k = \sum_{k=1}^{K} h_k x_k + v_k \tag{4}$$

B. LDS-OFDM

Much like in LDS-CDMA, signal spreading is carried out by spreading, zero-padding, and interleaving. Each users' generated chip is transmitted over a subcarrier belonging to the OFDM mapper where the superposed signal is modulated (Fig.1). Users that are using the same subcarrier are superimposed. Let the set of OFDM data symbols for the k^{th} user, sharing the subcarrier $n = [1, ..., N]$, be represented as

$$D_{n|k} = \left\{(k, i) : s_{i,n}^k \neq 0\right\} \tag{5}$$

where $s_{i,n}^k$ denotes the i^{th} row of the spreading signature matrix s at the n^{th} subcarrier for the k^{th} user. Let $b_k = [b_1, b_2, ..., b_K]$ be the set of user data; a transmitted symbol can be presented as

$$x_n^k = \sum_{(i,k)\in D_{n|k}}^{n=N,k=K} b_k s_{i,n}^k \tag{6}$$

As established in (4), the received signal can be denoted by

$$y_n = \sum_{(i,k)\in D_{n|k}}^{n=N,k=K} h_n^k x_n^k + v_n \tag{7}$$

C. SCMA

The SCMA encoding process takes the complex layered codeword i^{th} column of the j^{th} predefined codebook, design method discussed in [10], and uses it to spread the signal of the k^{th} user. Let the set of predefined codewords in each code book be $\mathbf{C}_{(i,j)}$ and the user data set be $b_k = [b_k, ..., b_K]$, the spread data set can be defined as

$$x_k = \sum_{i,j,k=1}^{K} \mathbf{C}_{(i,j)} b_k \tag{8}$$

Received signal can then be denoted as

$$y_k = \sum_{i,j,k=1}^{K} x_k h_k + v_k \tag{9}$$

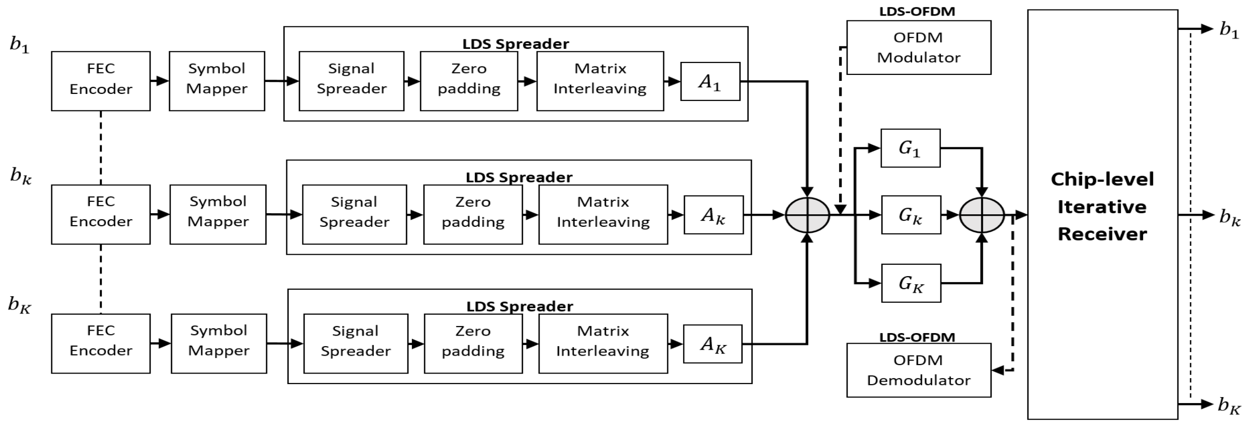

Fig. 1. LDS CDMA/OFDM System Model [2]

TABLE I
SIMULATION PARAMETERS FOR OFDM

Number of Users	16
Symbols Per Frame	53
FFT Length	64
Cyclic Prefix Length	16
Channel Model	AWGN
Modulation	16-QAM
Transmit Antennas	1

TABLE II
SIMULATION PARAMETERS FOR LDS-CDMA

Number of Users	16
Bits Per Signal	2
Hadamard Matrix Size	8x8
Channel Model	AWGN
Modulation	4-QAM

III. PERFORMANCE ANALYSIS UNDER AWGN CHANNEL

In this section, the performance of CD-NOMA techniques mentioned in Section II is analysed. OFDM is chosen as the OMA technique to be used as a base for comparison and is simulated in MATLAB using the predefined operator in the system library. The BER of each technique is measured over a range of SNR values while transmitting over an AWGN Channel. The simulation of each technique is carried out according to its respective simulation parameters. In order to ensure result accuracy, each technique runs one value of SNR for 5000 iterations. The bit/symbol error is computed for each iteration then averaged over the total number of iterations before moving on to the next SNR value. The total average error is then normalised to produce the error rate.

The SNR values range from 0 to a maximum of 20 dBs (with +1 increment). A system is considered to be in outage if even one user does not receive 50% of its message for CD-NOMA and more than or equal to 10.6 erroneous symbols at the output for OFDM. As fig.2 shows, OFDM achieves a BER performance of about 0.01 at approximately 18 dBs of signal to noise power while every CD-NOMA technique achieves the same or lower error rate while requiring much less signal power. LDS-CDMA at 0.01 BER with around 11 dBs, LDS-OFDM at 0.005 BER with 10 dBs, and SCMA at approximately 0 BER with less than 6 dBs. The outage performance of OFDM, as shown in fig.3, remains inoperable until the 15 dB mark unlike CD-NOMA which achieves vastly superior performance while in outage. With LDS-CDMA and LDS-OFDM arriving at 0.45% and 0.3% OP respectively with about 11 dBs and SCMA at approximatley 0% OP at less than 5 dBs.

TABLE III
SIMULATION PARAMETERS FOR LDS-OFDM

Number of Users	3
Bits Per Signal	2
Symbols Per Frame	8
Hadamard Matrix Size	8x8
Channel Model	AWGN
Mapping	BPSK
Modulation	OFDM
Cyclic Prefix Length	16
FFT Length	19
Number of Symbols	6

TABLE IV
SIMULATION PARAMETERS FOR SCMA

Number of Users	6
Codebooks	6
Codewords Per Book	4
Bits Per Signal	2
Channel Model	AWGN

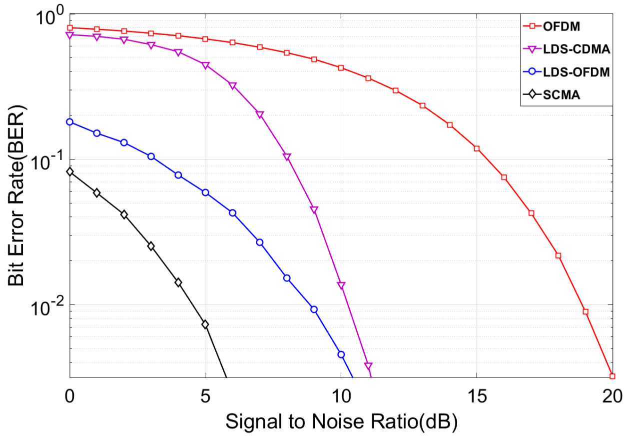

Fig. 2. BER for CD-NOMA Vs OMA

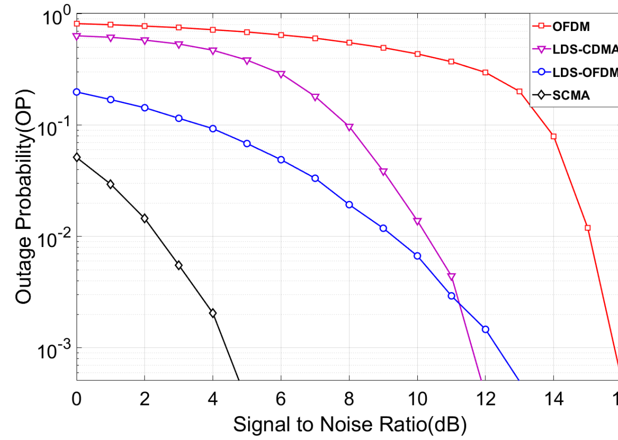

Fig. 3. Outage Performance for CD-NOMA Vs OMA

TABLE V
IMPLEMENTATION FEASIBILITY COMPARISON

	OFDM	LDS-CDMA	LDS-OFDM	SCMA
Encoding Complexity	Low	Low	Average	Very High
Decoding Complexity	Low	Average	Average	Average
Low-SNR Performance	Very Low	Average	High	Very High
High-SNR Performance	Very High	High	High	Very High
ISI	Very Low	Average	Low	Low
Receiver Complexity	Low	Low	Very High	Average
Overall Feasibility in Large Networks	High	Average	Low	Average

IV. CONCLUSION

This paper presented an overview of PD and CD NOMA, experimental simulations, and performance evaluations. NOMA superposes multiple users in the power domain, optimising the usage of available bandwidth by allowing subcarriers to accommodate multiple users, as opposed to dedicated frequency bands in OMA. The simulations have showcased the performance of NOMA and OMA scheme(s) in terms of their bit error rate and outage probability at a range of SNR values while transmitting over an AWGN channel. NOMA was revealed to be superior in terms of bit error as well as outage performance over OMA. Among the tested NOMA schemes, SCMA was shown to have the lowest bit error rate and outage probability at high interference channels and with low transmit power. Despite its highly complex design procedure for generating sparse spreading codewords, SCMA far outperforms other CD-NOMA schemes, making it the most likely candidate for focus in future research. Promising future directions for NOMA include: investigating receiver complexity in NOMA relative to OMA in order to improve on its implementation feasibility, combining the NOMA principle with MIMO in larger networks, investigating the efficacy of NOMA from an energy efficiency standpoint, and applying the co-op transmission scheme to NOMA in an attempt to increase diversity for each user which, in turn, may lead to a better outage performance.

REFERENCES

[1] Z. Chen, Z. Ding, X. Dai, and R. Zhang, “A mathematical proof of the superiority of NOMA compared to conventional OMA,” IEEE Trans. Commun., (submitted) Available on-line at arXiv:1612.01069.

[2] H. Sadia, M. Zeeshan and S. A. Sheikh, ”Performance analysis of downlink power domain NOMA under fading channels,” 2018 ELEKTRO, Mikulov, 2018, pp. 1-6.

[3] S. M. Raizul Islamet al., ”Power-Domain Non-Orthogonal Multiple Access (NOMA) in 5G Systems: Potentials and Challenges,” IEEE Communications Surveys and Tutorials, vol.PP, no.99, 25 Oct. 2016, pp. 1-1.

[4] Z. Ding, X. Lei, G. K. Karagiannidis, R. Schober, J. Yuan, V. K. Bhargava, ”A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends,”, “IEEE J. Select. Areas Commun.”, 35(10) pp. 2181-2195, Oct. 2017.

[5] Anass Benjebbour et al., ”Novel Low-Density Signature for Synchronous CDMA Systems Over AWGN Channel,“ in IEEE Transactions on Signal Processing, vol. 56, no. 4, pp. 1616-1626, April 2008.

[6] K. E. Ahmed and M. M. Farag, ”Enhanced Overloaded CDMA Interconnect (OCI) Bus Architecture for On-Chip Communication,” 2015 IEEE 23rd Annual Symposium on High-Performance Interconnects, Santa Clara, CA, 2015, pp. 78-87.

[7] L. Welch, ”Lower bounds on the maximum cross correlation of signals (Corresp.),” in IEEE Transactions on Information Theory, vol. 20, no. 3, pp. 397-399, May 1974.

[8] R. Hoshyar, R. Razavi, and M. Al-Imari, “LDS-OFDM: an efficient multiple access technique,” in Proc. IEEE 71st Vehicular Technology Conf. (VTC 2010-Spring), pp. 1–5.

[9] H. Nikopour and H. Baligh, “Sparse code multiple access,” in Personal Indoor and Mobile Radio Communications (PIMRC), 2013 IEEE 24th International Symposium on. IEEE, 2013, pp. 332–336.

[10] Taherzadeh, M., Nikopour, H., Bayesteh, A., and Baligh, H. “SCMA Codebook Design,” In Proc. IEEE Vehicular Technology Conference (VTC Fall), 2014, pp. 1-5.