Improving Performance of MC-CDMA Systems Using UTTCM Channel Coding

Ridha Ilyas Bendjillali[1], Mohammed Sofiane Bendelhoum[1], Elarbi Abderraouf, and Mohamed Rida Lahcene[2]

[1]*University Center Nour Bachir El Bayadh, El Bayadh, Algeria,*
[2]*University Center of Naama, El Bayadh, Algeria*

https://doi.org/10.26636/jtit.2024.2.1547

Abstract — Over the past decade, personal communications have witnessed exponential growth, fueled by the increasing number of connected users and the diversity of transmitted data types. This expansion necessitates a boost in the transmission systems' capacity to accommodate higher user numbers and data rates, simultaneously striving to optimize cost and complexity. Consequently, future communication systems are pivoting towards multi-carrier spread spectrum techniques (MC-CDMA), capitalizing on the robustness of OFDM multi-carrier transmissions against multipath propagation and leveraging the flexibility of the code division multiple access (CDMA) technique.
This study addresses data transmission quality-related concerns within an MC-CDMA system by implementing UTTCM error correction codes. These codes aim to enhance channel spectrum efficiency and mitigate error probability. Simulation results demonstrate that the proposed transmission scheme offers significant improvements in terms of bit error rate and signal-to-noise ratio, while maximizing the bandwidth shared among users. Additionally, the incorporation of such equalization techniques as zero forcing (ZF) and minimum mean square error (MMSE), ensures extensive compensation for the channel selectivity effect.

Keywords — channel coding, MC-CDMA, MSE, UTTCM, ZF

1. Introduction

The design of any mobile communication system involves addressing multiple access concerns, specifically how to enable numerous users to share a common physical medium [1]. Resource allocation in such systems can be accomplished through three distinct techniques: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA). CDMA has garnered significant attention from researchers due to its performance and is recognized as a key asset driving the evolution of mobile telephony. Additionally, competitive methods have emerged to ensure simultaneous data transmission, with orthogonal frequency division multiplexing (OFDM) standing out for its effective management of the propagation channel [2], [3].

The success of OFDM and CDMA techniques has stimulated the idea of integrating them within a single transmission system to develop potential solutions that meet the requirements of future cellular mobile communication systems and enhance their performance. This integration initially led to the development of multi-carrier code division multiple access (MC-CDMA). The use of OFDM modulation in a CDMA context offers the advantage of elongating the duration of transmitted symbols. Despite their performance, these systems are characterized by drawbacks in terms of interference between codes, carriers, and users.

When integrating MC-CDMA systems with a robust channel encoder, unpunctured turbo trellis coded modulation (UTTCM) demonstrates superior spectrum efficiency and error probability performance. Consequently, this subject has gained substantial attention from various research groups, resulting in significant advancements in these techniques. Since the introduction of turbo channel codes, numerous studies have showcased their performance and optimization objectives using binary modulations. However, concerns regarding high-data-rate transmission while adhering to a predefined bandwidth have led some researchers to consider implementing turbo codes solely for highly spectral-efficient modulations [4]. Consequently, UTTCM is the most powerful commercially available error-correction coding technique. As it is based primarily on iterative coding techniques at the reception side, its efficiency becomes more critical in the Rayleigh channel, as it is capable of protecting transmissions against mobile radio channel fading, as seen in fourth-generation mobile telephony (LTE) [5].

The primary goal of operators consisting in maximizing the number of users highlights the significant contribution of multi-user detection in enhancing the overall spectrum efficiency of MC-CDMA systems [6], [7]. In cases of unknown or time-varying channels, perfect verification of the Nyquist criterion is unfeasible, and residual interference may be mitigated through equalization schemes, such as zero-forcing or minimum mean square error (MMSE) [8]–[10].

In this paper, Section 2 presents a comprehensive review of prior research on MC-CDMA and UTTCM. It underscores different facets of MC-CDMA and UTTCM techniques, highlighting their individual contributions and potential integration possibilities. Section 3 presents a detailed description of the research methodology employed, elucidating the approaches utilized in investigating the performance and efficiency of MC-CDMA integrated with UTTCM. Section 4 presents the experimental findings, offering empirical evidence, and analyzes the results derived from the research conducted.

Section 5 concludes the paper by summarizing the contributions made to enhancing mobile communication systems through the integration of MC-CDMA and UTTCM [11]. It also emphasizes their potential for superior performance in terms of spectral efficiency and error correction capabilities.

2. Related Work

The research involving MC-CDMA systems encompasses several studies focusing on enhancing efficiency, detection, equalization, and compensation characteristics of these systems. The investigation performed by Bendelhoum *et al.* [12] delves into improving a downlink MC-CDMA system for efficient image transmission, focusing on image compression and transmission efficiency.

Fateh *et al.* [13] evaluate the performance of MC-CDMA systems employing single-user detection techniques, while Zidane *et al.* [14] conduct a comparative study between adaptive and blind algorithms for channel identification and equalization in MC-CDMA.

Additionally, studies by Zidane *et al.* [15] and Safi *et al.* [16] explore compensation methods for fading channels and utilize higher-order cumulants for equalization in MC-CDMA. Furthermore, Frikel *et al.* [17] propose a channel identification scheme that uses chaos for a multicarrier code division multiple access system.

Meanwhile, research conducted by Abderraouf *et al.* [18] focuses on applying iterative coding systems utilizing UTTCM to improve the performance of 4G-LTE mobile radio communication networks. This involves enhancing data transmission efficiency within fourth-generation networks by implementing UTTCM and iterative decoding systems.

3. Methods

3.1. MC-CDMA Technique

The MC-CDMA technique, introduced in [19], has been subjected to extensive comparisons with DS-CDMA systems, demonstrating its effectiveness over other approaches thanks to combining CDMA access methods and OFDM modulation [20]. Consequently, MC-CDMA systems have emerged as promising candidates for the 4th generation of mobile radio systems [21]. Spread spectrum techniques and multi-carrier modulations offer numerous advantages, including the inherent information confidentiality of the spread spectrum [22], lower power spectral density of the transmitted signal, and the ability to accommodate multiple accesses through code division. With multi-carrier modulations, the emphasis is placed on achieving spectral efficiency and robustness against inter-symbol and inter-channel interference.

This discussion covers the MC-CDMA concept, signal structure, coding methodologies, and detection approaches.

Tab. 1. Optimal 8-state TCM encoders for Gray and Ungerboeck-Gray mapping.

Number of states	m	h_0	h_1	h_2	h_3	h_4	Mapping
8	2	13	05	10	/	/	G
			11	04	/	/	UG

3.2. Structure of the UTCM Encoder

The UTTCM encoder, as proposed in [23]–[25], consists of two TCM encoders concatenated with an interleaver, each with a rate of $\frac{m}{m+1}$.

For a spectral efficiency of m [bps], the mapper receives 2^{m+2} bits, m systematic bits from the 1st, along with a parity bit, and a de-interleaved parity bit from the 2nd encoder, resulting in the utilization of a 2^{m+2} point constellation.

For a spectral efficiency of 2 [bits/s/Hz], each encoder operates at a rate of 2/3 with 8 states and a 16-QAM, constellation, employing Gray (G) and Ungerboeck-Gray (UG) mapping [26]. The free distance of the UTTCM set is $d_f = \sqrt{3.6}$.

Table 1 illustrates the optimal 8-state TCM encoders for G and UG mapping, displaying the number of states, mapping details, and respective values of h_0 to h_4.

3.3. Structure of the Proposed MC-CDMA System

The structure of the proposed transmission scheme is shown in Fig. 1. The MC-CDMA signal [27] is generated through a serial concatenation of the classical DS-CDMA and OFDM. The MC-CDMA modulator disperses each user's data in the frequency domain. Specifically, each chip of the direct spreading sequence of a data symbol modulates a subcarrier. In contrast to DS-CDMA's serial transmission, MC-CDMA transmits the spreading chips of a data symbol in parallel, through different subcarriers. The transmitted signal's nature aligns with the transmission channel's input and allows the receiver to perform the reverse operation. The observed signal potentially closely resembles the message issued by the source.

The transmitting signal corresponding to the k-th data bit of the m-th user is given by:

$$s_m(t) = \sum_{i=0}^{N-1} a_m(k) c_m(i) \cos(\psi_i) p_{T_b}(t - kT_b) \ , \tag{1}$$

where

$$\psi_i = 2\pi f_c t + 2\pi \frac{F}{T_b} t \ , \ i = 0, 1, \ldots, N-1 \ . \tag{2}$$

$c_m(1), c_m(2), \ldots, c_m(N-1)$ represents the spreading code of the m-th user, p_{T_b} is the unit amplitude gate function on the interval $[0, T_b]$, F_c is the carrier frequency, and F is the spacing between the subcarriers. The transfer function of the fading channel considered for the m-th user at frequency p_{T_b} $f_c + i\frac{F}{T_b}$ is:

$$H_m\left(f_c + i\frac{F}{T_b}\right) = \rho_{m,i} e^{j\theta_{mi}} \ , \tag{3}$$

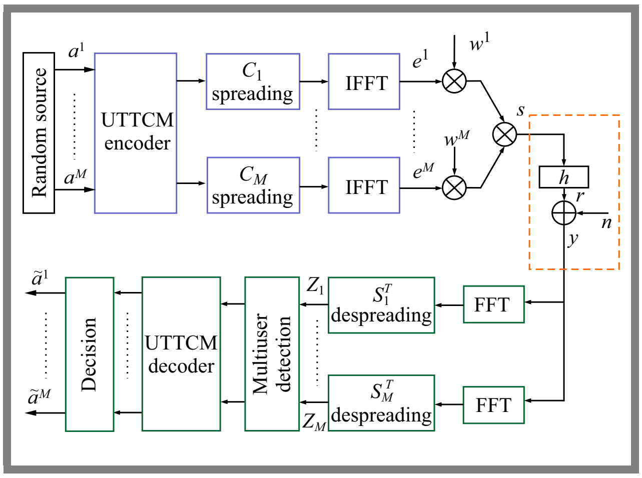

Fig. 1. Structure of the simulated transmission chain.

where $\rho_{m,i}$ and θ_{mi} are the random amplitude and phase of the fading channel, respectively.

The received signal, when m users are active, is:

$$r(t) = \sum_{m=0}^{M-1}\sum_{i=0}^{N-1} \rho_{m,i} a_m(k) c_m(i) \cos\varphi_i + n(t) \ , \tag{4}$$

where $\varphi_i = 2\pi f_c t + 2\pi \frac{F}{T_b} t + \theta_{m,i}$. The channel's effect is included in $\rho_{m,i}, \theta_{m,i}$ and $n(t)$. Assuming perfect channel estimation and perfect synchronization at the receiver, the detected signal (the decision variable) is given by:

$$v_0 = a_0(k) \sum_{i=0}^{N-1} \rho_{0,i}\, d_{0,i} + B_{int} + n(t) \ . \tag{5}$$

The decision variable consists of three terms, the first one corresponds to the desired signal component ($m = 0$) and the second corresponds to the interference:

$$B_{int} = \sum_{m=0}^{M-1}\sum_{i=0}^{N-1} \rho_{m,i}\, d_{0,i} a_m(k) c_0(i) \cos\breve{\theta}_{m,i} \ , \tag{6}$$

where $\breve{\theta}_{m,i} = \theta_{m,i} - \theta_{0,i}$.

It is important to note that this term cancels out in an ideal channel ($\rho_{m,i} = 1$ and $\theta_{m,i} = 0$).

The final term corresponds to noise:

$$n = \sum_{i=0}^{N-1} \int_{kT_b}^{(k+1)T_b} \frac{2}{T_b} n(t) c_0(i)\, d_{0,i} \cos(\breve{\phi}_i) dt \tag{7}$$

or

$$\breve{\phi}_i = 2\pi f_c t + 2\pi \frac{F}{T_b} t + \breve{\theta}_{0,i} \ .$$

4. Results and Discussion

Table 2 presents a comprehensive summary of the parameters used in the Matlab simulation.

4.1. Channel and System Configuration

Proakis B channels were used as the designated transmission channels throughout the study. The length of the spreading code (Walsh-Hadamard) was kept constant at ($N_{fft} = 16$). Variations in the number of users (N_{user}) were examined, spanning values from 1 to 8. For these simulations, both the minimum square error equalizer (MSE) and the zero-forcing equalizer were employed. Figures 2 through 4 in the subsequent sections portray BER vs. SNR curves, illustrating the comparative performance of DS-CDMA and MC-CDMA systems.

Tab. 2. Parameters used in the simulation.

Parameter	Value
Transmitted data size	$M = 128$ octets
OFDM block	N_{fft}
Spreading codes	Walsh-Hadamard codes of N_{fft} length
Cyclic prefix	$N_{cp} = N_{fft}/4$
Equalizer	ZF and MSE equalizer
Channel model	Proakis B channel
Number of users	N_{user}
Modulation	Used modulation is MAQ-16
Decoding of the UTTCM encoder	MAP

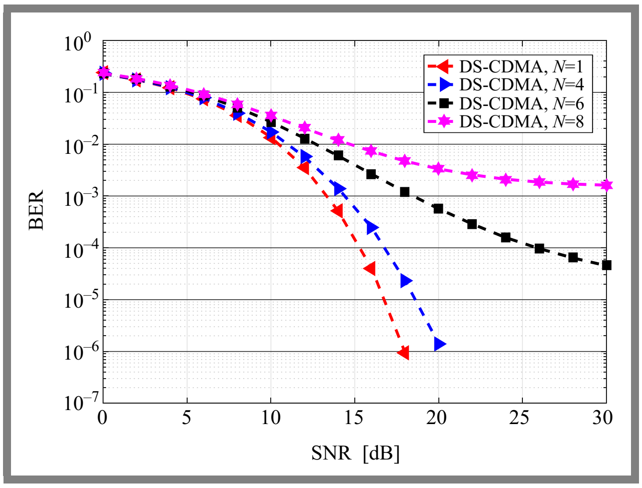

Fig. 2. BER as a function of DS-CDMA SNR, with MSE equalizer, Proakis B channel $N_{fft} = 16$ and $N_{user} = 1$, 4, 6, and 8.

Figures 5–7 depict the simulation results for two types of equalizers, namely the zero forcing equalizer (ZF) and the minimum squared error equalizer (MSE), and for a number of users equal to (1, 4, 5, 6, and 8) – for two types of systems, i.e. DS-CDMA and MC-CDMA. A common observation across all scenarios is an increase in BER becoming evident as the number of users grows. However, it is noteworthy that the equalizers do not exhibit identical performance characteristics. Hence, this comparative analysis aims to determine the optimal solution for each scenario. Therefore:

- the MSE detector shows robustness against the glare phenomenon, outperforming the ZF equalizer,

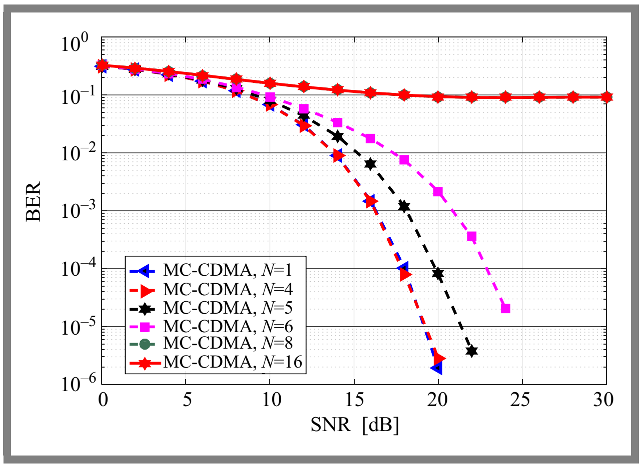

Fig. 3. BER as a function of MC-CDMA SNR, with ZF equalizer, Proakis B channel, $N_{fft} = 16$ and $N_{user} = 1$, 4, 5, 8, and 16.

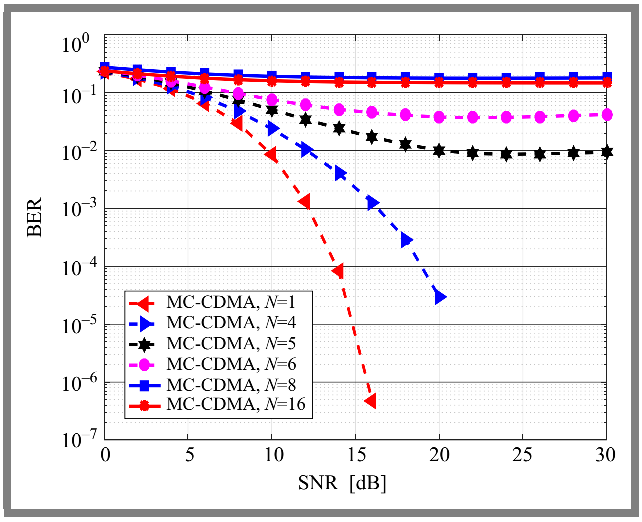

Fig. 4. BER as a function of MC-CDMA SNR, with MSE equalizer, Proakis B channel, $N_{fft} = 16$ and $N_{user} = 1$, 4, 5, 6, 8, 16.

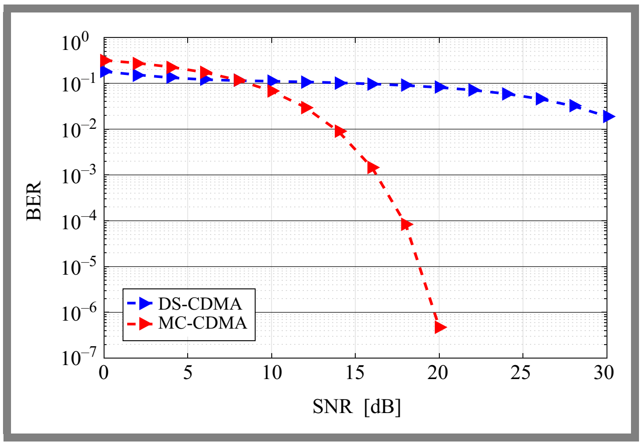

Fig. 5. Error rates as a function of SNR; comparison of MC-CDMA and DS-CDMA systems, with ZF equalizer, Proakis B channel, $N_{fft} = 16$ and $N_{user} = 1$.

- MC-CDMA exhibits better performance compared to DS-CDMA, due to the multi-carrier OFDM system's increased resistance to fading effects.

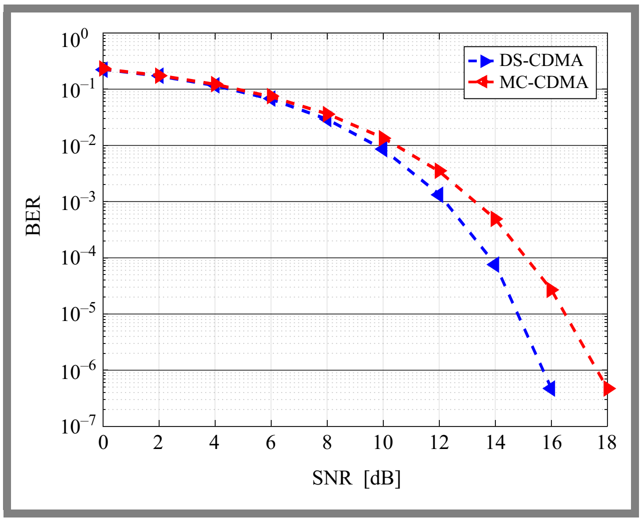

Fig. 6. BER as a function of SNR; comparison of MC-CDMA and DS-CDMA systems, with a MSE equalizer, Proakis B channel, $N_{fft} = 16$ and $N_{user} = 1$.

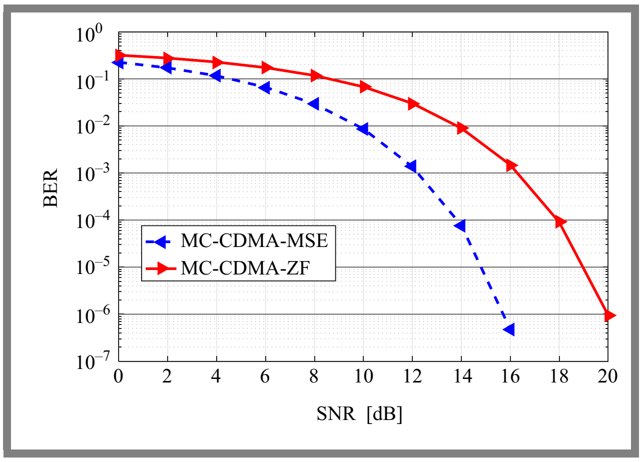

Fig. 7. BER as a function of SNR; comparison of MC-CDMA systems with a quadratic error equalizer and MC-CDMA and a ZF equalizer, Proakis B channel, $N_{fft} = 16$ and $N_{user} = 1$.

Furthermore, the contrast between OFDM-CDMA and DS-CDMA illustrates better fading resistance of the OFDM-CDMA system, achieved due to its multi-carrier OFDM structure. These findings offer practical installation-related insights allowing to get the most out of real-life wireless communication systems.

4.2. Performance of MC-CDMA System Using UTTCM Channel Coding

The UTTCM encoder utilized in this study, acting as the channel encoder, is characterized by 2/3 efficiency, has 3 memories, and operates with a 128-byte data block size. The Walsh-Hadamard codes employed have a length of N_{fft}. Simulations were conducted on the Proakis B channel [28], with variations in the number of users (N_{user} = 1, 4, 5, 6, and 8). Simulation results corresponding to these parameters are depicted in the following figure.

The results presented in Figs. 8 and 9 demonstrate that the MSE detector outperforms the ZF equalizer. Figures 9 and

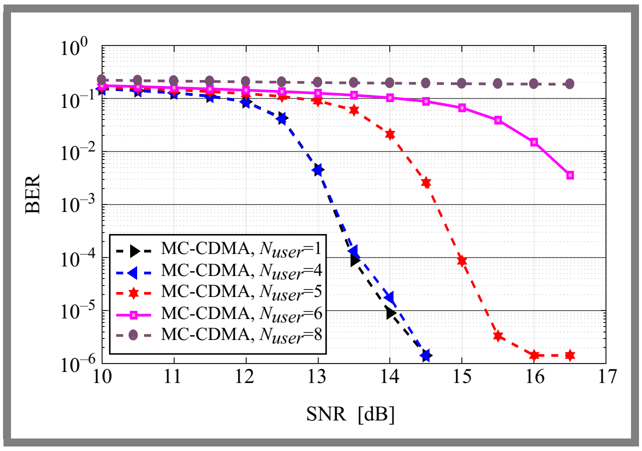

Fig. 8. Performance of an MC-CDMA system with UTTCM encoder, Proakis B channel, ZF equalizer, $N_{iter} = 4$, $M = 128 \times 8 = 1024$, and $N_{fft} = 16$.

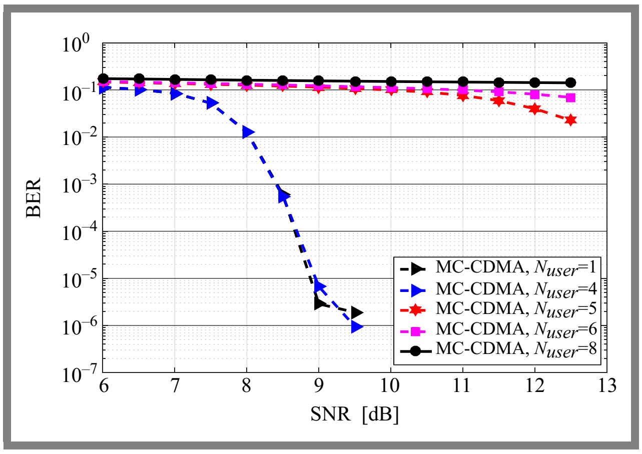

Fig. 9. Performance of an MC-CDMA system with UTTCM encoder, Proakis B channel, MSE equalizer, $N_{iter} = 4$, $M = 128 \times 8 = 1024$, and $N_{fft} = 16$.

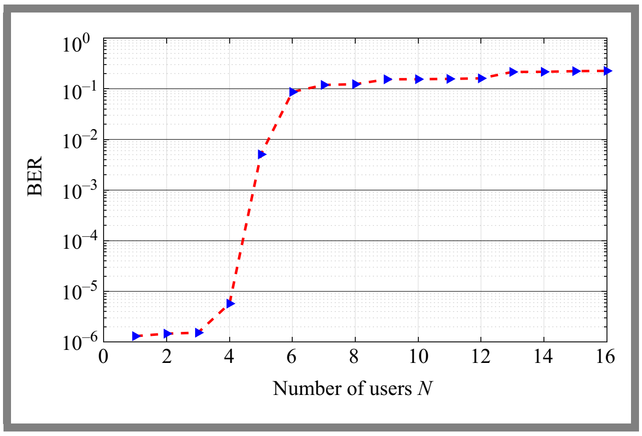

Fig. 10. Performance of an MC-CDMA system with UTTCM encoder, Proakis B channel, MSE equalizer, SNR = 9 dB, $N_{iter} = 4$, $M = 128 \times 8 = 1024$, and $N_{fft} = 16$.

10 illustrate that the performance of the MC-CDMA system is enhanced by:

- increasing SNR,
- decreasing the number of users (N_{user}).

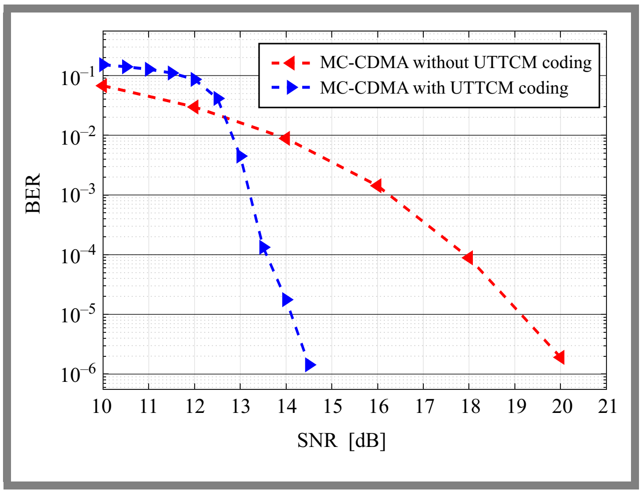

Fig. 11. Performance comparison of an MC-CDMA system with and without UTTCM encoder, Proakis B channel, zero forcing equalizer, $N_{iter} = 4$, $M = 128 \times 8 = 1024$, $N_{fft} = 16$ and $N_{user} = 4$.

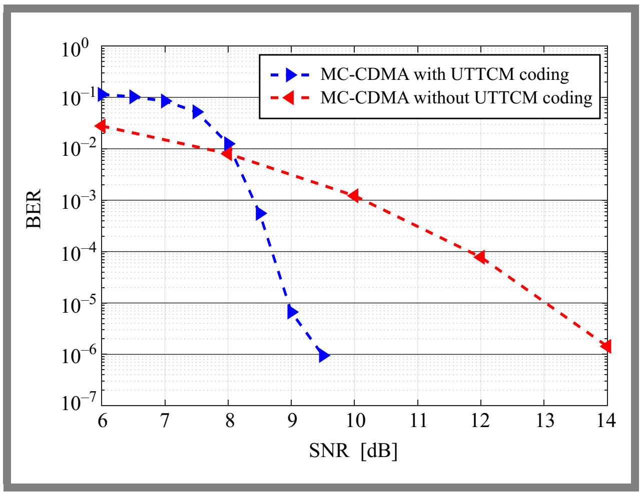

Fig. 12. Performance comparisons of an MC-CDMA system with and without UTTCM encoder, Proakis B channel, MSE equalizer, $N_{iter} = 4$, $M = 128 \times 8 = 1024$, $N_{fft} = 16$, and $N_{user} = 4$.

Figures 11 and 12 indicate that the BER improvement attributed to the use of the UTTCM channel encoder reaches 10^{-5}. Comparing the performance of the MC-CDMA system without the UTTCM encoder with that of a system with the UTTCM encoder shows an improvement of approximately 4.88 dB in Fig. 11 and 4 dB in Fig. 12. Hence, employing the UTTCM encoder leads to better performance in the MC-CDMA system.

More thorough understanding of the performance of the MC-CDMA system is gained by analyzing it after encoding with UTTCM. This culminates the results shown in Figs. 8 to 12. The MSE detector is better than the ZF equalizer, and the system's performance is enhanced with an increase in SNR and a decrease in the number of users (N_{user}).

Moreover, the comparison manifests a notable improvement in BER when using the UTTCM channel encoder, boosting it by 4 to 4.88 dB. The consequence of integrating the UTTCM encoder has an immense effect on improving the performance of the MC-CDMA system.

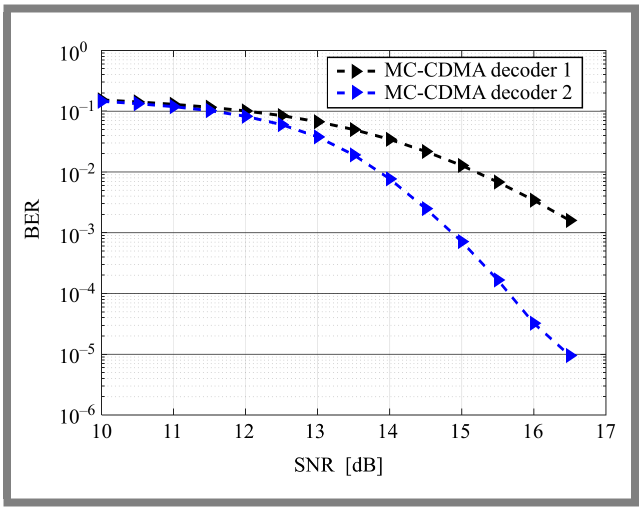

Fig. 13. Comparison of performance of decoder 1 and decoder 2 of a UTTCM encoder associated with an MC-CDMA system, Proakis B channel, MSE equalizer, $M = 128 \times 8 = 1024$, $N_{fft} = 16$, and $N_{user} = 4$.

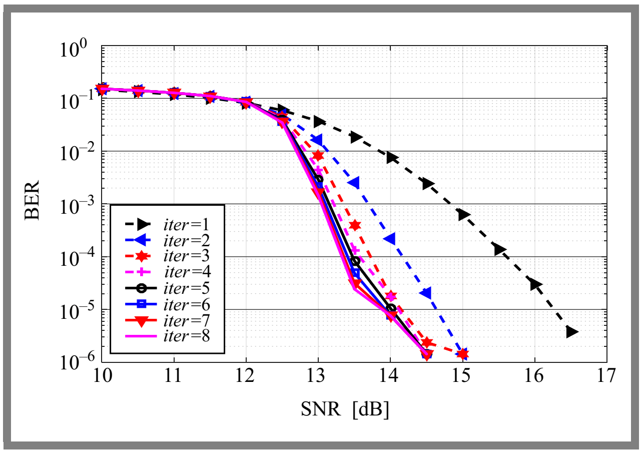

Fig. 14. Performance of an MC-CDMA system with UTTCM encoder, Proakis B channel, ZF equalizer, $M = 128 \times 8 = 1024$, $N_{fft} = 16$, and $N_{user} = 4$.

4.3. Impact of the Iterative UTTCM Decoding Process on the MC-CDMA System

To investigate the impact of implementing the iterative decoding process, simulations were conducted using a UTTCM encoder made up of two elementary 8-state encoders, each with 2/3 efficiency and pseudo-random interleaving. MAP was the decoding algorithm employed. Figure 13 illustrates the relationship between decoders 1 and 2.

The transfer characteristic of extrinsic information is now known for a SISO decoder. During iterative decoding, the output of decoder 1 serves as the input of decoder 2 and vice versa. At sufficiently high signal-to-noise ratios, the two curves converge, indicating the exchanged extrinsic information for each iteration, starting from zero mutual information.

This method allows to track the exchanged extrinsic information between the two decoders throughout the iterations, providing insights into the convergence and mutual information exchange in iterative decoding processes.

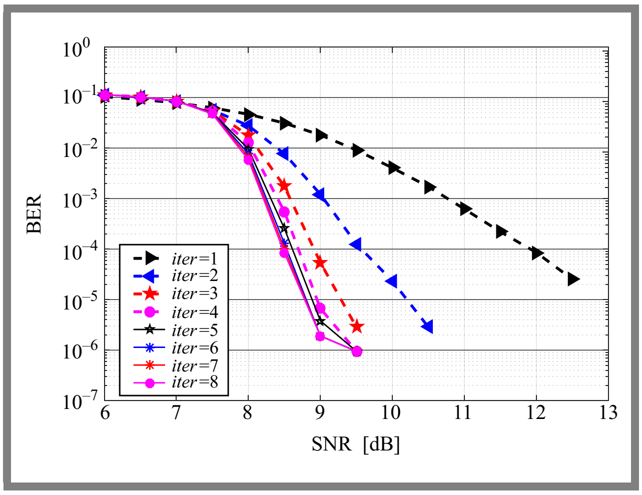

Fig. 15. Performance of an MC-CDMA system with UTTCM encoder, Proakis B channel, MSE equalizer, $M = 128 \times 8 = 1024$, $N_{fft} = 16$, and $N_{user} = 4$.

Figure 15 illustrates the performance of an 8-state UTTCM, with a varying number of iterations. One may observe that the performance of an MC-CDMA system improves by: enhancing SNR, increasing the number of iterations.

This enhancement in performance, attributed to higher SNR and additional iterations, underscores the influence of the iterative process on the MC-CDMA system's efficiency when utilizing the UTTCM encoder.

In addition to the above analysis, the impact of implementing the iterative decoding process on the MC-CDMA system with the UTTCM encoder is investigated. Simulations conducted using a UTTCM encoder composed of two elementary 8-state encoders, along with the MAP decoding algorithm, shed light on the relationship between decoders 1 and 2, as depicted in Fig. 13.

The convergence of the transfer characteristic of extrinsic information for a SISO decoder is observed, indicating the exchanged extrinsic information between the decoders throughout the iterations. This method allows for tracking the mutual information exchange between the decoders, providing insights into the convergence and efficiency of the iterative decoding process.

5. Conclusion

This research is dedicated to integrating novel transmission systems and amalgamating multiple technologies, such as OFDM multi-carrier modulation, CDMA code division multiple access, and UTTCM iterative channel coding techniques. The comprehensive simulations manifest that the fusion of the advanced MC-CDMA communication technique with UTTCM encoder channel coding successfully addresses system constraints related to throughput, robustness, congestion, and spectral efficiency for the chosen transmission channel.

Moreover, employing MMSE and ZF equalization techniques within the MC-CDMA system demonstrates a significant potential to mitigate the effects of channel selectivity. Consequently, the proposed scheme performs better in terms of optimizing spectral utilization, overcoming interference, and ensuring reliable data transmission across various channel conditions. Integrating UTTCM iterative encoding techniques notably contributes to achieving higher data rates, while preserving data integrity and fidelity. Furthermore, adaptive equalization strategies, particularly MMSE and ZF, play a pivotal role in addressing channel distortions, thus ensuring robust communication in environments susceptible to fading and interference.

References

[1] V. Le Nir, "Study and Optimization of Multi-antenna Systems Associated with Multi-carrier Modulations", PhD thesis, Institut National des Sciences Appliquées de Rennes, France, 2004 (https://theses.eurasip.org/theses/190/study-and-optimization-of-multi-antenna-systems/read/).

[2] M.S. Bendelhoum, M.R. Lahcene, F. Menezla, and A. Benali, "Medical Images Transmitting Using MC-CDMA System", *2019 6th International Conference on Image and Signal Processing and Their Applications (ISPA)*, Mostaganem, Algeria, 2019 (https://doi.org/10.1109/ISPA48434.2019.8966824).

[3] M. S. Bendelhoum, M.R. Lahcene, F. Menezla, and E. Abderraouf, "Studying and Modeling the Performance of the TCM-STBC Systems in the Rayleigh Channel", Journal of Telecommunication and Information Technology, no. 1, pp. 1–7, 2021 (https://doi.org/10.26636/jtit.2021.147020).

[4] A. Chemsa, "Modulation with Iterative Coding for a Non-Gaussian Noise Channel", PhD thesis, Mohamed Khider University of Biskra, Algeria, 2016.

[5] A. Kumar and J. Saxena, "Detection Schemes for MC-CDMA (4G) Mobile System: A Review", *Computer Science and Telecommunications*, vol. 45, no. 1, pp. 49–62, 2015 (http://gesj.internet-academy.org.ge/download.php?id=2522.pdf).

[6] F. Portier, "High Spectral Efficiency Wireless Systems for 4th Generation Multi-antenna and Multi-carrier Mobile Communications", PhD thesis, Institut National des Sciences Appliquées de Rennes, France, 2007.

[7] S. Hara and R. Prasad, "Overview of Multicarrier CDMA", *IEEE Communications Magazine*, vol. 35, no. 12, pp. 126–133, 1997 (https://doi.org/10.1109/35.642841).

[8] A.S. Mahore, B. Singh, and P.S. Tanwar, "A Review 4G System QAM MC-CDMA Higher Data Rates Transmission Systems in Impulsive Noise", *International Journal of Electrical, Electronics and Computer Engineering*, vol. 3, no. 1, pp. 177–182, 2014.

[9] A. Mardhiyya, R.P. Astuti, and N.M. Adriansyah, "A Multiuser Interference Mitigation Scheme in MC-CDMA Uplink with CFO Estimation-MMSE FEQ Technique", *International Conference on Signals and Systems (ICSigSys)*, Bali, Indonesia, 2017 (https://doi.org/10.1109/ICSIGSYS.2017.7967070).

[10] B.A. Kenney, A.J. Majid, H. Moradi, and B. Farhang-Boroujeny, "Frequency Domain Multi-user Detection for Single Carrier Modulation with Cyclic Prefix", *GLOBECOM 2020 – 2020 IEEE Global Communications Conference*, Taipei, Taiwan, 2020 (https://doi.org/10.1109/GLOBECOM42002.2020.9322612).

[11] R.I. Bendjillali, M.S. Bendelhoum, A. A. Tadjeddine, and M. Kamline, "Deep Learning-Powered Beamforming for 5G Massive MIMO Systems", *Journal of Telecommunications and Information Technology*, no. 4, pp. 38–45, 2023 (https://doi.org/10.26636/jtit.2023.4.1332).

[12] M.S. Bendelhoum, A. Djebbari, I. Boukli-Hacene, and A. Taleb-Ahmed, "An Improved Downlink MC-CDMA System for Efficient Image Transmission", *Journal of Telecommunications and Information Technology*, no. 4, pp. 5–16, 2017 (https://doi.org/10.26636/jtit.2017.110917).

[13] R. Fateh, A. Darif, and S. Safi, "Performance Evaluation of MC-CDMA Systems with Single User Detection Technique using Kernel and Linear Adaptive Method", *Journal of Telecommunications and Information Technology*, no. 4, pp. 1–11, 2021 (https://doi.org/10.26636/jtit.2021.151621).

[14] M. Zidane, S. Safi, M. Sabri, A. Boumezzough, and M. Frikel, "Adaptive Algorithms Versus Higher Order Cumulants for Identification and Equalization of MC-CDMA", *Journal of Telecommunications and Information Technology*, no. 3, pp. 53–62, 2014 (https://doi.org/10.26636/jtit.2014.3.1034).

[15] M. Zidane, S. Safi, and M. Sabri, "Compensation of Fading Channels Using Partial Combining Equalizer in MC-CDMA Systems", *Journal of Telecommunications and Information Technology*, no. 1, pp. 5–11, 2017 (https://doi.org/10.26636/jtit.2017.1.644).

[16] S. Safi, M. Frikel, A. Zeroual, and M. M'Saad, "Higher Order Cumulants for Identification and Equalization of Multicarrier Spreading Spectrum Systems", *Journal of Telecommunications and Information Technology*, no. 2, pp. 74–84, 2011 (https://doi.org/10.26636/jtit.2011.2.1148).

[17] M. Frikel, S. Safi, B. Targui, and M. M'Saad, "Channel Identification Using Chaos for an Uplink/Downlink Multicarrier Code Division Multiple Access System", *Journal of Telecommunications and Information Technology*, no. 4, pp. 91–97, 2010 (https://doi.org/10.26636/jtit.2010.4.1116).

[18] E. Abderraouf, M.R. Lahcene, M.S. Bendelhoum, A.A. Tadjeddine, and Y. Djeldjeli, "Application of Iterative Decoding Systems (UTTCM) to 4G-LTE Mobile Radio Communication Network", *Sebha University Journal of Pure & Applied Sciences*, vol. 21, no. 4, 2022 (https://doi.org/10.51984/JOPAS.V21I4.2113).

[19] T. Pollet, M. Van Bladel, and M. Moeneclaey, "BER Sensitivity of OFDM Systems to Carriers Frequency Offset and Wiener Phase Noise", *IEEE Transactions on Communications*, vol. 43, pp. 191–193, 1995 (https://doi.org/10.1109/26.380034).

[20] T. Pollet, M. Moeneclaey, I. Jeanclaude, and H. Sari, "Carrier Phase Jitter Sensitivity for Single-carrier and Multi-carrier QAM Systems", *IEEE Symposium on Communications and Vehicular Technology in the Benelux*, Louvain la Neuve, Belgium, 1994 (https://doi.org/10.1109/SCVT.1994.574161).

[21] H.C. Mora, N.O. Garzón, and C. de Almeida, "On the Cellular Spectral Efficiency of MC-CDMA Systems with MMSE Multiuser Detector Employing Fractional and Soft Frequency Reuse", *AEU – International Journal of Electronics and Communications*, vol. 84, pp. 34–45, 2018 (https://doi.org/10.1016/j.aeue.2017.11.011).

[22] R.D. Kumar and K.S. Vishvaksenan, "Interference Cancellation in Cognitive Radio-based MC-CDMA System Using Pre-coding Technique", *Journal of Supercomputing*, vol. 76, pp. 1–15, 2020 (https://doi.org/10.1007/s11227-018-2503-6).

[23] A. Bassou and A. Djebbari, "Contribution to the Improvement of the Performance of Trellis-coded Modulation", *WSEAS Transactions on Communications*, vol. 6, no. 2, pp. 307–311, 2007.

[24] A. Bassou, A. Djebbari, and M. Benaissa, "Design of Unpunctured Turbo Trellis-coded Modulation", *AEU International Journal of Electronics and Communications*, vol. 67, no. 3, pp. 223–232, 2013 (https://doi.org/10.1016/j.aeue.2012.08.005).

[25] E. Abderraouf, A. Bassou, and M.R. Lahcene, "Higher Performance and Lower Complexity Turbo Decoding Scheme for 4G-LTE Using Unpunctured Turbo Trellis-coded Modulation", *Indonesian Journal of Electrical Engineering and Computer Science (IJEECS)*, vol. 18, no. 1, pp. 351–360, 2020 (https://doi.org/10.11591/ijeecs.v18.i1.pp351-360).

[26] M.R. Lahcene, A. Bassou, M. Beladgham, and A.T. Ahmed, "On the Employment of Unpunctured Turbo-Trellis Coded Modulation Channel Coding to Improve the Performance of WiMax System", *International Journal on Communications Antenna and Propagation (IRECAP)*, vol. 8, no. 3, pp. 248–256, 2018 (https://doi.org/10.15866/irecap.v8i3.13609).

[27] A.K. Gnanasekar and V. Nagarajan, "Efficient MAI Cancellation Scheme in MC-DS-CDMA Using SIC", *International Journal on Parallel Programming*, vol. 48, pp. 416–430, 2020 (https://doi.org/10.1007/s10766-018-0575-9).

[28] J.G. Proakis, *Digital Communications*, Mc Graw-Hill: New York, 4th ed., 1024 p., 2000 (ISBN: 9780072321111).

Ridha Ilyas Bendjillali, Ph.D.
Laboratory of Electronic Systems, Telecommunications and Renewable Energies, Department of Electrical Engineering
https://orcid.org/0000-0003-2465-8192
E-mail: r.bendjillali@cu-elbayadh.dz
University Center Nour Bachir El Bayadh, El Bayadh, Algeria
https://www.cu-elbayadh.dz

Mohammed Sofiane Bendelhoum, Ph.D., Associate Professor
Laboratory of Electronic Systems, Telecommunications and Renewable Energies, Department of Electrical Engineering
https://orcid.org/0000-0002-9789-8712
E-mail: m.bendelhoum@cu-elbayadh.dz
University Center Nour Bachir El Bayadh, El Bayadh, Algeria
https://www.cu-elbayadh.dz

Elarbi Abderraouf, Ph.D.
https://orcid.org/0009-0004-5449-1156
E-mail: elarbiabderraouf12@gmail.com

Mohamed Rida Lahcene, Ph.D.
Laboratory of Electronic Systems, Telecommunications and Renewable Energies, Department of Electrical Engineering
https://orcid.org/0009-0001-9581-8870
E-mail: lahcen@cuniv-naama.dz
University Center of Naama, El Bayadh, Algeria
https://www.cuniv-naama.dz