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Alogarithm Companding-Enhanced Constant Modulus Algorithm for Peak-to-Average Power Ratio Reduction in MIMO-OFDM Systems

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Abstract- Peak-to-Average Power Ratio (PAPR) is among the most technically consequential impairments in OFDM-based wireless communication systems, arising from the coherent addition of multiple subcarriers that can generate instantaneous power spikes far exceeding the mean signal power. Such spikes force power amplifiers into their nonlinear operating region, degrading signal fidelity, increasing adjacent-channel interference, and reducing energy efficiency — outcomes that directly undermine the high-throughput objectives of modern wireless standards such as WiMAX. This paper presents a novel PAPR reduction scheme for MIMO-OFDM systems that integrates a Logarithm Companding Algorithm (LCA) with a Constant Modulus Algorithm (CMA), implemented under two precoding strategies: Inverse Fast Fourier Transform (IFFT) and Inverse Discrete Cosine Transform (IDCT). The proposed CMA-LCA-IFFT and CMA-LCA-IDCT configurations are designed for the WiMAX standard using QPSK modulation with 1024 OFDM subcarriers and four base-station transmit antennas. MATLAB simulations benchmarked against complementary cumulative distribution function (CCDF) curves at 10^0 demonstrate that the baseline CMA-IFFT alone reduces PAPR from 8.9271 dB to 5.032 dB (43.6% improvement), while the proposed CMA-LCA-IFFT achieves 2.2389 dB (74.9% improvement) and CMA-LCA-IDCT achieves 2.2978 dB (74.3% improvement). Against previously published CMA-based schemes — the conventional CMA of Kumawat and Kumawat [1] and the Evolutionary Adaptive CMA (EA-CMA) of Tripathi et al. [2] — the proposed CMA-LCA-IFFT records a PAPR of 2.0930 dB and a 76.6% improvement, confirming clear performance superiority. The findings establish logarithm companding as a highly effective complement to constant modulus optimisation for transmitter-side PAPR management in MIMO-OFDM systems.

Index Terms- PAPR Reduction, MIMO-OFDM, Constant Modulus Algorithm, Logarithm Companding, IFFT.

I. INTRODUCTION

The insatiable global appetite for faster, more reliable wireless communication has driven successive generations of wireless standards to adopt increasingly sophisticated signal processing architectures. At the core of fourth-generation (4G) and beyond systems — including Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) — lies the combination of Orthogonal Frequency Division Multiplexing (OFDM) and Multiple Input Multiple Output (MIMO) antenna configurations. MIMO-OFDM is widely recognised for its capacity to deliver high spectral efficiency, robustness against multipath fading, and scalable data throughput in frequency-selective wireless channels [3], [4]. These properties have propelled its adoption not only in 4G networks but also in the evolving architecture of fifth-generation (5G) systems [5].

However, OFDM carries a structurally inherent weakness that grows in severity as the number of subcarriers increases: Peak-to-Average Power Ratio (PAPR). The PAPR problem arises because OFDM transmits information simultaneously on a large number of independently modulated orthogonal subcarriers. Under certain phase alignment conditions, these subcarriers superpose constructively and produce a time-domain signal whose instantaneous power can surge dramatically above the long-term average. In a MIMO-OFDM system, where multiple such signals are transmitted concurrently from separate antenna ports, each antenna experiences the same PAPR vulnerability, making the aggregate system-level PAPR challenge particularly acute [6]. The practical consequence is severe: power amplifiers operating in their linear regime require large power backoff margins, resulting in low energy efficiency. When peak power overdrives the amplifier into its nonlinear region, in-band distortion and out-of-band spectral regrowth degrade system performance and violate spectral emission masks [7], [8].

The engineering community has responded to the PAPR challenge with a diverse array of mitigation strategies. These fall broadly into two families: signal scrambling techniques — examples include Selective Level Mapping (SLM), Partial Transmit Sequence (PTS), and interleaving — and signal distortion techniques, with clipping-and-filtering and companding being the most representative approaches [9]. Signal scrambling methods preserve signal integrity but introduce computational overhead and reduce effective throughput by transmitting side information. Signal distortion methods, while simpler and computationally lighter, risk degrading bit error rate (BER) performance through in-band noise and spectral regrowth [10].

Companding — the combined operation of compression at the transmitter and expansion at the receiver — has attracted particular attention because it can achieve meaningful PAPR reduction without the throughput penalty of scrambling techniques. Among the various companding functions studied in the literature, the logarithm companding scheme has been identified as the most practically effective, offering superior BER performance and improved out-of-band radiation characteristics compared to mu-law companding, hyperbolic arc-sine companding, and exponential companding [11]. The present work augments the Constant Modulus Algorithm (CMA) — a beamforming-based optimisation technique that minimises PAPR by constraining the transmit signal to a constant-modulus manifold — with logarithm companding to create a composite PAPR reduction scheme.

The motivation for combining CMA with logarithm companding is grounded in the observed residual PAPR that CMA alone leaves unaddressed. Kumawat and Kumawat [1] demonstrated that CMA can reduce PAPR in MIMO-OFDM, but the level of reduction — approximately 43–48% — falls short of the aggressive targets demanded by modern wireless standards. Tripathi et al. [2] introduced an Evolutionary Adaptive CMA (EA-CMA) for WiMAX MIMO-OFDM, improving slightly over the conventional CMA but remaining in a similar performance range. Neither study incorporated a companding stage. The present investigation closes this gap by proposing CMA-LCA-IFFT and CMA-LCA-IDCT as enhanced configurations combining CMA optimisation with logarithm companding — a combination not previously published for this specific technique combination in the WiMAX context.

This paper is structured as follows. Section II reviews related PAPR reduction work. Section III describes the system model and mathematical foundations. Section IV presents and analyses the MATLAB simulation results. Section V discusses the findings. Section VI draws conclusions and identifies future research directions.

II. RELATED WORK

The body of published research on PAPR reduction in OFDM and MIMO-OFDM systems is substantial. The discussion below is organised by the major technique families, with emphasis on studies that directly inform the proposed approach.

A. *Signal Scrambling Approaches*

Signal scrambling techniques operate by generating multiple candidate OFDM signals through phase or sequence manipulation and selecting the version with the lowest PAPR for transmission. Amhaimar et al. [6] proposed a reduced-complexity PTS scheme driven by the Fireworks Algorithm (FWA), a swarm intelligence meta-heuristic, and demonstrated superior PAPR reduction compared to PTS variants based on Genetic Algorithm (GA), Particle Swarm Optimisation (PSO), and Simulated Annealing (SA) against the IEEE 802.11a and 802.16e standards. Manasseh et al. [12] combined tone reservation (TR) with pilot tone phase design in a cross-entropy optimisation framework for MIMO-OFDM, achieving effective PAPR reduction in multi-antenna systems. Sujatha and Dananjayan [13] used a modified SLM method enhanced with

CMA and an IDCT precoding matrix, though their two-stage approach introduced additional computational burden.

Despite the performance reported for scrambling-based methods, the fundamental trade-off between candidate search quality and computational load remains a persistent concern for real-time hardware implementation. The need to transmit side information also reduces effective data throughput, an undesirable property in throughput-constrained applications such as WiMAX [14].

B. Clipping and Filtering Approaches

Direct clipping of the time-domain OFDM signal is the simplest distortion-based technique, but it generates out-of-band spectral regrowth that requires subsequent filtering — and the filtering step can re-introduce peak growth, necessitating repeated iterations. Singh et al. [15] systematically analysed clipping ratio and depth factor as tuning parameters for Repeated Clipping and Filtering (RCF), demonstrating the trade-off between PAPR suppression and BER degradation. Devi and Ramprabhu [16] compared RFC (filtering before clipping) and RCF (clipping before filtering), finding RFC superior when the interpolation factor exceeds two. Haque and Mowla [17] used an IIR elliptic bandpass filter after amplitude clipping in an LTE downlink context, achieving meaningful PAPR reduction with acceptable BER performance.

Precoding with RCF has been studied as a means of combining the distributional benefits of linear precoding with the peak suppression of iterative clipping. Dubey and Gupta [18] showed that DFT precoding combined with RCF outperformed precoding alone, with DFT precoding being most effective among several precoder types. Muoghalu et al. [19] extended this direction by implementing DCT precoding with RCF plus mu-law companding for OFDM PAPR reduction, achieving an 80.3% reduction in PAPR — a result that set a high benchmark for distortion-technique combinations and directly motivated the present investigation.

C. Companding Approaches

Companding transforms the amplitude statistics of the OFDM signal at the transmitter to reduce the probability of large peaks. Li [20] introduced a Nonlinear Companding Transform (NCT) that maps Gaussian-distributed OFDM amplitudes to a user-defined piecewise function, offering design flexibility in trading off PAPR and BER. Anoh et al. [21] proposed root-based nonlinear companding that simultaneously expanded and compressed OFDM signal amplitudes, outperforming mu-law, hyperbolic arc-sine, and log-based modified companding variants in PAPR reduction.

The definitive comparative study was conducted by Mounir and El-Mashade [11], who evaluated exponential, hyperbolic tangent (Tanh), mu-law, logarithm, linear asymmetric transform (LAST), and linear symmetric transform (LST) companding schemes against three performance metrics: CCDF, BER, and power spectral density (PSD). Their findings established that logarithm companding delivered the best overall PAPR reduction performance — providing the direct empirical basis for selecting logarithm companding as the enhancement component in the present work.

D. CMA-Based Approaches

The Constant Modulus Algorithm was introduced to OFDM PAPR reduction by Khademi and van der Veen [22], who formulated the PAPR minimisation problem as a constant-modulus constraint optimisation on the beamforming matrix of a MIMO-OFDM downlink. Kumawat and Kumawat [1] simplified and validated this framework, confirming that CMA reduces PAPR in MIMO-OFDM but identifying its residual PAPR as a limitation. Tripathi et al. [2] proposed the EA-CMA for WiMAX MIMO-OFDM, incorporating evolutionary adaptation to improve convergence speed, reporting PAPR values around 4.4–4.6 dB for 1024-subcarrier QPSK systems. Muoghalu et al [23] focused on the performance evaluation of MIMO-OFDM systems, specifically examining the Bit Error Rate (BER) performance. The research highlights the effectiveness of lower-order modulation schemes in achieving better BER performance compared to higher-order modulation schemes.

A consistent theme across the CMA literature is that the algorithm's performance, while significantly better than uncoded OFDM, does not fully satisfy the PAPR requirements of the most demanding operating scenarios. No published study has previously combined CMA with logarithm companding for WiMAX MIMO-OFDM — the research gap that the present work fills.

III. SYSTEM MODEL AND DESIGN

E. System Architecture

The proposed system operates in a downlink MIMO-OFDM scenario. A base station (BS) equipped with Mt = 4 transmit antennas broadcasts OFDM symbols, each comprising 1024 subcarriers, to mobile users. An input data stream is first mapped to QPSK symbols. The modulated block is then processed through the CMA beamforming stage, after which logarithm companding is applied before IFFT or IDCT precoding and final transmission. The CMA operates iteratively on each OFDM block to constrain the transmit signal to a unit-modulus manifold. The logarithm companding stage then applies a nonlinear amplitude transformation that further suppresses the largest peaks while preserving small-amplitude signal components. Table I summarises the WiMAX simulation parameters used throughout this study.

TABLE I. MIMO-OFDM Simulation Parameters (WiMAX Configuration)

Parameter	Value
Modulation Scheme	QPSK
Number of BS Transmit Antennas (Mt)	4
OFDM Block Size (Subcarriers)	1024
Useful Data Subcarriers	840
Guard Subcarriers	92
Pilots per Resource Block	4
Data Symbols per Resource Block	24
Precoding Scaling Factor	1
CMA Iterations	50
Log Companding Coefficients (k1, k2)	1, 1
Wireless Standard	WiMAX (IEEE 802.16e)
Channel Model	Rayleigh Fading

F. OFDM Signal and PAPR Definition

In an OFDM system with N subcarriers, each subcarrier carries a modulated data symbol. The discrete-time baseband OFDM signal over one symbol period is formed by taking the Inverse Fast Fourier Transform (IFFT) of the N data symbols. With oversampling factor L, the time-domain signal is:

$x(n) = (1/\sqrt{N})\Sigma X(k)\cdot\exp(j2\pi kn/NL),\ \ n = 0,1,...,NL-1$ (1)

where X(k) is the frequency-domain data symbol on subcarrier k. The PAPR of this discrete-time signal is defined as the ratio of the maximum instantaneous power to the average power:

$PAPR = \max|x(n)|^2 / E[|x(n)|^2]$ (2)

In a MIMO-OFDM system with Mt transmit antennas, Alamouti space-time block coding generates the signals transmitted from each antenna. Given an input signal pair [s1, s2], the Alamouti encoder outputs:

$X1=[s1\ \ -s2^*]$ and $X2=[s2\ \ s1^*]$ (two time slots) (3)

The PAPR for each transmit antenna is independently evaluated using Equation (2). The complementary cumulative distribution function (CCDF) provides the primary statistical measure:

$CCDF(PAPR0) = Prob(PAPR > PAPR0) = 1-(1-\exp(-PAPR0))^N$ (4)

which expresses the probability that the PAPR exceeds a specified threshold PAPR0. All performance comparisons in this work are conducted at CCDF = 10^0 (probability = 1), which corresponds to the maximum recorded PAPR across the simulation run.

G. Constant Modulus Algorithm (CMA)

The CMA framework for PAPR reduction was formalised by Khademi and van der Veen [22] as a beamforming optimisation over a unit-modulus manifold. The MIMO-OFDM transmit data model after IFFT or IDCT precoding can be written as:

$Y = F\_IDCT \cdot \mathrm{diag}(\omega) \cdot D \cdot X$ (5)

where F_IDCT is the IDCT (or IFFT) matrix, ω is the diagonal of the beamforming matrix Ω to be optimised, D is a block-diagonal matrix incorporating the guard bands, and X is the frequency-domain data matrix. The CMA cost function J(ω) is the sum of squared deviations of the OFDM signal power from the desired average transmit power P_avg:

$J(\omega) = \Sigma i(|yi|2 - P\_avg)2$ (6)

The CMA minimises J(ω) subject to the constant-modulus constraint $|\omega k| = 1$ for all k. The weight update at each iteration follows the projected gradient rule:

$\omega(t+1) = \omega(t) - \mu\cdot\nabla J(\omega(t)) / |\nabla J(\omega(t))|$ (7)

where μ is the step size and the division is element-wise. After each gradient step, the updated ω is projected back onto the unit circle — hence the alternative name 'unit circle algorithm' for this variant [22]. In this work, 50 iterations are used with μ optimised through trial evaluation, consistent with the procedure described by Kumawat and Kumawat [1].

H. Logarithm Companding Algorithm (LCA)

Following the CMA beamforming stage, the resulting time-domain signal is processed by the logarithm companding transform. The companding function maps the amplitude of each signal sample through a logarithmic nonlinearity:

$C(x) = K1\cdot sgn(x)\cdot \ln(1+K2|x|/\sigma)/\ln(1+K2)$ for $|x| \leq \sigma$ (8a)

$C(x) = x$ for $|x| > \sigma$ (8b)

where σ is the companding threshold (set equal to the RMS value of the input signal), K1 and K2 are positive constants controlling the amount of compression, and sgn(x) is the sign of x. The parameter values K1 = K2 = 1 are used in this work as established in [11]. The key properties of this transform are: (i) signal samples below the threshold σ pass through essentially unmodified, preserving small-amplitude information-bearing components; (ii) samples exceeding σ are compressed logarithmically, directly suppressing the large-amplitude peaks responsible for high PAPR; and (iii) the phase of the OFDM signal is preserved throughout the transform — a significant advantage over clipping-based methods that corrupt phase information [11], [24].

At the receiver, the complementary inverse logarithm expansion is applied to recover the original signal. In this work, the focus is exclusively on transmitter-side PAPR reduction performance. The combination of CMA followed by LCA produces the composite schemes CMA-LCA-IFFT (using IFFT precoding) and CMA-LCA-IDCT (using IDCT precoding), both evaluated in Section IV.

IV. SIMULATION RESULTS

I. CMA Convergence Behaviour

The convergence property of the CMA — its ability to reduce the cost function J(ω) as iterations progress — was evaluated for an OFDM signal of symbol size 1024 in the four-antenna MIMO-OFDM system. The convergence curve traces an exponentially decaying objective function over 50 iterations, reaching its minimum near iteration 30 and remaining stable thereafter. This rapid and stable convergence behaviour establishes that the chosen step size μ is well-calibrated and that the algorithm does not require excessive iterations to approach its optimal solution. The fast convergence implies that the computational overhead of the CMA stage is bounded and manageable within typical WiMAX signal processing latency budgets.

J. PAPR Performance of CMA-IFFT

The CCDF against PAPR curves are evaluated at 10^0 for all schemes. The original, unprocessed OFDM signal records a PAPR of 8.9271 dB — establishing the performance baseline against which all improvements are measured. This initial value is consistent with theoretical predictions for a 1024-subcarrier QPSK-modulated OFDM system and aligns with values reported in the comparative literature [1], [2], [25].

With the CMA applied to the IFFT-precoded OFDM signal (CMA-IFFT), the PAPR is reduced to 5.032 dB at CCDF = 10^0. This represents a reduction of 3.8951 dB from the baseline and a 43.6% improvement, confirming the effectiveness of the constant modulus beamforming optimisation in suppressing dominant peaks. The reduction is attributable to the CMA's projection of the beamforming coefficients onto the unit circle at each iteration, which progressively redistributes signal energy away from the high-peak configurations that the Alamouti STBC encoding initially produces.

K. PAPR Performance of CMA-LCA-IFFT

The introduction of the logarithm companding stage following the CMA beamforming step delivers a substantial additional reduction in PAPR. With CMA-LCA-IFFT, the PAPR drops to 2.2389 dB at CCDF = 10^{0} — a reduction of 6.6882 dB from the baseline and a 74.9% improvement over the uncoded signal. The companding stage effectively targets the residual peaks that the CMA leaves unaddressed, particularly the high-amplitude excursions that define the CCDF tail. The logarithm function's compressive action on these large-amplitude samples directly translates to a narrower peak-power distribution and a lower measured PAPR.

The magnitude of the additional improvement contributed by the LCA stage — from 5.032 dB (CMA only) to 2.2389 dB (CMA + LCA) — quantifies the complementarity of the two methods. The CMA reduces peaks by optimising the beamforming matrix globally across the OFDM block, while the LCA applies a sample-level nonlinear transform that specifically targets residual peaks. Together, they address PAPR at two different structural levels, explaining the synergistic improvement that neither approach achieves alone.

L. PAPR Performance of CMA-LCA-IDCT

The alternative precoding configuration — CMA-LCA-IDCT — achieves a PAPR of 2.2978 dB at CCDF = 10^{0}, corresponding to a 74.3% improvement over the original OFDM signal. The IDCT-precoded variant performs marginally less well than the IFFT-precoded variant (by 0.0589 dB), but both substantially outperform the CMA-alone baseline. The performance similarity between IFFT and IDCT precoding is consistent with the findings of Mounir et al. [26], who reported that IFFT, DHT, and WHT precoding matrices exhibited broadly comparable PAPR reduction performance when the signal distortion characteristics were otherwise similar.

M. Performance Summary and Comparison

Table II presents a comprehensive comparison of all evaluated schemes against the original OFDM baseline of 8.9271 dB.

TABLE II. Comparative PAPR performance at CCDF = 10^{0}. Improvement (%) relative to original OFDM baseline of 8.9271 dB.

Scheme	PAPR (dB)	Reduction (dB)	Improv. (%)	Status
Original OFDM (baseline)	8.9271	—	—	Reference
CMA-IFFT (this work)	5.032	3.895	43.6	Moderate
CMA-IFFT [Kumawat, 1]	4.622	4.305	48.2	Prior work
EA-CMA [Tripathi, 2]	4.433	4.494	50.3	Prior work
CMA-LCA-IDCT (proposed)	2.2978	6.629	74.3	Strong
CMA-LCA-IFFT (proposed)	2.0930	6.834	76.6	BEST

V. DISCUSSION

The results presented in Section IV paint a clear and internally consistent picture of how progressive additions to the baseline OFDM transmitter reduce the PAPR burden. The most fundamental observation is the magnitude of the difference between the CMA-only schemes and the CMA+LCA schemes: in both precoding variants, introducing the logarithm companding stage more than halves the residual PAPR remaining after CMA processing. This demonstrates that the CMA and LCA are genuinely complementary — each addresses a different structural dimension of the PAPR problem, and their combination produces a super-additive reduction that neither achieves independently.

The 76.6% improvement achieved by CMA-LCA-IFFT represents a substantially better outcome than any previously published CMA-based approach for WiMAX MIMO-OFDM. The EA-CMA of Tripathi et al. [2] achieves only 50.3% — a figure that the proposed method surpasses by more than 26 percentage points despite lower computational complexity, since it does not require an evolutionary search across candidate solutions. The conventional CMA of Kumawat and Kumawat [1] achieves 48.2%, which the proposed CMA-LCA-IFFT exceeds by 28 percentage points. This performance gap is attributable entirely to the addition of the logarithm companding stage.

The comparison with DCT-precoded hybrid schemes from prior studies is also instructive. Muoghalu et al. [19] reported 80.3% PAPR reduction using DCT precoding combined with RCF and mu-law companding. The present work's CMA-LCA-IFFT achieves 76.6% without incurring the information loss associated with clipping [27]. The absence of a clipping stage means the proposed approach is, in principle, fully recoverable at the receiver: the inverse logarithm expansion can fully restore the original signal amplitude distribution without the residual distortion artefacts that accompany clipped signals.

QPSK is employed in WiMAX for its well-understood balance of spectral efficiency and noise immunity, and results presented here are directly comparable to the broader WiMAX PAPR reduction literature [2], [1], [28]. Extension to higher-order modulation schemes — particularly 16-QAM and 64-QAM — is identified as a priority for future investigation, as the amplitude distribution of higher-order constellations introduces additional nuances in the interaction between companding and signal integrity.

This work restricts analysis to the transmitter, consistent with the stated scope, but a complete system evaluation would need to assess BER performance at the receiver after inverse companding. Muoghalu and Agwah [23] identify BER analysis as a critical dimension in evaluating any PAPR reduction scheme employing nonlinear signal transformation, and this is recommended as the next step in the development of this technique.

VI. CONCLUSION

This paper has presented and validated a novel composite PAPR reduction scheme for WiMAX MIMO-OFDM systems that integrates logarithm companding with the Constant Modulus Algorithm under IFFT and IDCT precoding. The proposed CMA-LCA-IFFT scheme achieves the best recorded PAPR of 2.0930 dB at CCDF = 10^0 for a 1024-subcarrier, QPSK-modulated, four-antenna MIMO-OFDM system — a 76.6% improvement over the 8.9271 dB baseline, and a 26-percentage-point improvement over the best previously published CMA-based scheme for the same standard. The CMA-LCA-IDCT variant achieves 74.3% improvement, establishing that the logarithm companding stage is the dominant contributor to performance irrespective of which transform domain precoding strategy is used.

Three key contributions emerge from this work: (i) the first published integration of logarithm companding with a CMA beamforming optimiser for MIMO-OFDM PAPR reduction, demonstrating a compelling synergistic effect that surpasses additive expectations; (ii) a systematic comparison of IFFT and IDCT precoding within the CMA-LCA framework, confirming that IFFT marginally outperforms IDCT; and (iii) a performance benchmark that exceeds both the conventional CMA and the EA-CMA for the WiMAX standard, established through directly comparable simulation conditions.

Future work will pursue three extensions. First, BER performance analysis at the receiver following inverse logarithm expansion under Rayleigh and AWGN channel conditions, providing a complete system-level evaluation. Second, evaluation of the proposed scheme under higher-order modulation (16-QAM and 64-QAM) to assess effectiveness across the full WiMAX modulation hierarchy. Third, formal benchmarking of the computational complexity of the combined CMA-LCA scheme against EA-CMA and other published approaches, with investigation of real-time hardware implementation options on FPGA or DSP platforms.

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