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Abstract*—In this paper, the problem of peak-to-average power ratio (PAPR) reduction of orthogonal frequency division multiplexing (OFDM) signals is investigated in the context of second generation of digital video broadcasting for terrestrial transmission (DVB-T2) and the American digital video broadcasting standard ATSC3.0. As a multicarrier modulation technique is characterized by a high PAPR of the transmitted signal and OFDM is prone to non-linear (NL) effects of power amplifiers. DVB-T2 and ATSC3.0 have adopted a gradient-based tone reservation (TR) PAPR reduction technique which is based on an iterative process where, at each iteration, a predefined kernel is used to reduce one peak in time domain. Recently, a new TR PAPR reduction technique termed individual carrier allocation for multiple peaks (ICMP), based on a novel kernel definition has been proposed. However, it suffers from latency issues in ATSC3.0 and higher modes of DVB-T2. So, we propose another novel TR technique, grouped ICMP (GICMP). The simulation results show that GICMP offers better performance than the gradient-based DVB-T2 algorithm. Furthermore, it not only yields the same performance as ICMP but also has less latency.

***Index Terms*—OFDM, Peak-to-Average Power Ratio, Power Control, DVB-T2, Tone Reservation, kernel phase optimization, latency, non-linear PA.**

I. Introduction

During the last three decades, multicarrier modulation (MCM) schemes have attracted a lot of attention among the scientific community in the field of telecommunications and terrestrial broadcasting. Till date, orthogonal frequency division multiplexing (OFDM) is the most widespread MCM scheme. OFDM has been extensively deployed in wireless communication systems such as DVB, WiFi, WiMAX and LTE, primarily for its advantages in frequency selective channels. However, as any MCM signal, OFDM exhibits a high peak-to-average power ratio (PAPR), which is a severe drawback.

The power amplifier (PA) is an essential component in the modern communication systems. Unfortunately, it is an analog component and is inherently non-linear (NL). Signals with high amplitude fluctuations, as in the case of MCM systems, pose a serious challenge to the RF design of PAs. In order to get rid of the amplified signal distortion, the PA is made to operate in its linear region, which has very poor energy efficiency. The presence of high peaks cause in-band (IB) and out-of-band (OOB) interferences when the MCM signals are amplified in the non-linear region of the PA. IB distortions cause inter-carrier interference while OOB distortions lead to interference with adjacent channels and the breaking of the spectral mask.

The PA linearity and energy efficiency are two vital parameters for any multicarrier wireless transmitter and especially for high power ones as used for TV broadcasting or macro base stations of 4G cellular networks. This has motivated many works in literature aiming at reducing on one hand the PAPR of the transmitted multicarrier signals and on the other hand the non-linearity introduced by the PA itself.

In recent years, tone reservation (TR) techniques [1], one among many PAPR reduction techniques, has been selected in various standards such as digital video broadcasting - second generation DVB-T2 [2] and the American Advanced Television Systems Committee (ATSC3.0) standard [3], for PAPR reduction. Unfortunately, the gradient-based TR algorithm adopted by the DVB-T2 standard and described in [2] does not offer a sufficient performance-complexity trade-off to be implemented in today's DVB-T2 modulators. That is why, to the best of our knowledge, the TR adoption in the world of the DVB-T2 commercial modulator suppliers is very low.

In this paper, we propose a novel PAPR TR reduction technique based on a kernel signal, which is simple to implement and compatible with the DVB-T2 standard. This proposed kernel is defined to deal with the reduction of multiple peaks at each iteration while optimizing the phase computation of each reserved subcarrier. Already based on this new kernel, a PAPR reduction technique, named individual carrier allocation for multiple peaks (ICMP) has been proposed in [4]. However, it cannot be applicable to ATSC3.0 and higher modes of DVB-T2. So, in this paper, we propose a modified version of this algorithm named as grouped ICMP (GICMP), which improves the performance of ICMP in terms of latency and hardware implementation. An analysis is then carried out showing that the new algorithm offers a very good performance/latency tradeoff. The simulations confirm the very high potential of this new algorithm, which is fully compatible with existing DVB-T2 and ATSC3.0 standards.

The rest of the paper is organized as follows: Section II reminds the main PAPR minimization issues and the power

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control constraint. In Section III, the new kernel definition is presented and ICMP TR algorithm is discussed. Then, the novel GICMP algorithm is proposed. Section IV deals with the performance of the proposed solution, based on simulation results. Finally, conclusions are drawn in Section V.

II. Reminder on PAPR minimization issues

In this section the PA model used in the paper is introduced. Then, the PAPR issue is discussed along with, the general idea behind TR and power control.

A. Overview of OFDM signal structure

Let $\mathbf{X} = [X_0, \ldots, \ldots, X_{N-1}]$ be a sequence of complex symbols to be transmitted over the N subcarriers of a DVB-T2 OFDM system. The baseband continuous-time model of the OFDM transmitted signal with a symbol period T can be defined as follows

$$x(t) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi \frac{kt}{NT}}, 0 \leq t < NT. \qquad (1)$$

B. PA model

Let us assume that $x(t)$ and $y(t)$ are the base-band equivalent of PA input and output respectively. With an ideal PA, the output signal is an amplified input signal with a linear gain. However, in a NL PA model, $y(t)$ can be represented as

$$y(t) = G(x(t))e^{j\phi_x(t)} \qquad (2)$$

where

- $\phi_x(t)$ is the phase of the input signal $x(t)$,
- $G(x(t))$ is the complex gain of the output signal $y(t)$.

The gain $G(x(t))$ is a function of the input voltage of the PA, $|x(t)|$ and is defined as

$$G(x(t)) = F_a(|x(t)|).e^{jF_p(|x(t)|)} \qquad (3)$$

where, $F_a(.)$ and $F_p(.)$ are the classical amplitude-to-amplitude (AM/AM) and amplitude-to-phase (AM/PM) conversion characteristics respectively.

In this paper, we consider Rapp model of PA [5]. This model does not apply a phase change to the input signal and assumes a linear performance for low amplitudes of the input signal. The AM/AM and AM/PM conversion characteristics of the Rapp model are

$$F_a(|x(t)|) = \frac{|x(t)|}{\left(1 + \left(\frac{|x(t)|}{v_{sat}}\right)^{2p}\right)^{\frac{1}{2p}}}, \; F_p(|x(t)|) = 0 \qquad (4)$$

where

- v_{sat} is the input saturation voltage of the PA,
- p is the knee factor.

The smoothness of transition from the linear region to the saturation region can be controlled by the factor p. The AM/AM conversion characteristic is illustrated in Fig. 1. In that figure, it can be noted that as the value of the knee factor increases the Rapp model approaches the soft envelope limiter [6].

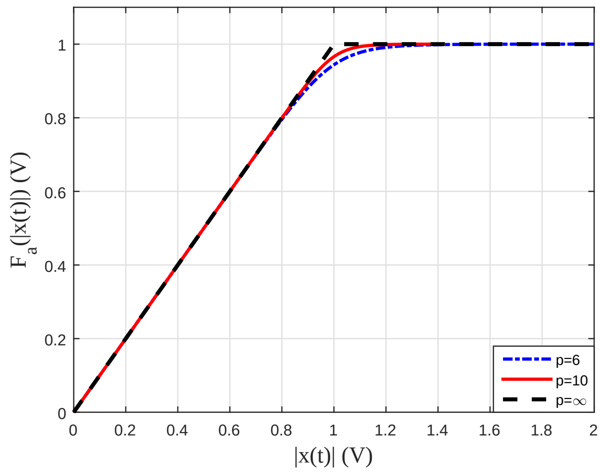

Fig. 1: AM/AM conversion characteristic of Rapp model of PA.

C. PAPR analysis

The PAPR is a random variable that is an important parameter in measuring the sensitivity of a NL PA, when a non-constant envelop input needs to be transmitted. The PAPR of the continuous-time base-band signal $x(t)$ transmitted during a symbol period T is defined by

$$PAPR_{x(t)} = \frac{\max_{0 \leq t \leq T} |x(t)|^2}{\frac{1}{T}\int_0^T |x(t)|^2.dt} \qquad (5)$$

The complementary cumulative density function (CCDF) of PAPR is a useful parameter to analyze the PAPR, which is defined as the probability that the PAPR of the discrete-time signal exceeds a given threshold that is denoted by γ and thereby it can be evaluated as $Pr\{PAPR_{s(t)} \geq \gamma\}$. However, CCDF alone is not sufficient to predict the NL effects of PA on signals as it does not take into account any additional peaks of lower amplitude. In this regard, modulation error ratio (MER) gives additional insights for performance evaluations. The European Telecommunications Standards Institute (ETSI) defines the MER as one of the measurement guidelines for DVB systems. The MER is defined in dB as [7]

$$MER\{\mathbf{X}, \widehat{\mathbf{X}}\} = 10\log_{10}\left(\frac{\|\mathbf{X}\|_2^2}{\left\|\mathbf{X} - \widehat{\mathbf{X}}\right\|_2^2}\right), \qquad (6)$$

where $\mathbf{X}$ is the ideal symbol vector measured at the input of the amplifier, $\widehat{\mathbf{X}}$ is measured at the output of the PA and $\|.\|_2$ denotes Euclidean norm.

D. General idea behind PAPR reduction by TR

The idea behind TR is to isolate energy used to cancel large peaks to a predefined set of subcarriers [1]. Let R be the subcarriers (or tones) that are reserved for PAPR reduction and $\mathcal{B}$ be the set of the peak reduction tones (PRT) locations. We will not transmit any data in these PRT locations. Thus, the PRTs do not carry any useful information and are orthogonal to

TABLE I: Size of R for different modes in DVB-T2 and ATSC3.0†.

MODE	1K	2K	4K	8K	16K	32K
N	1024	2048	4096	8192	16384	32768
R	9	18	36	72	144	288

† ATSC3.0 has only 8K, 16K and 32K modes.

the data tones. Stated mathematically, the resulting transmitted signal will be

$$x(t) = d(t) + c(t), 0 \leq t < \infty, \tag{7}$$

where, $c(t)$ is the peak cancellation signal and $d(t)$ is the data signal (i.e. related to data only). $x(t)$ can be represented in frequency domain as $X[k]$, given by

$$\mathbf{X} = \begin{cases} D[k], & k \in \mathcal{B}^c \\ C[k], & k \in \mathcal{B} \end{cases} \tag{8}$$

where, $D[k] = 0$, for $n \in \mathcal{B}$, $C[k] = 0$, for $n \in \mathcal{B}^c$ where $\mathcal{B}^c$ is the complement set of $\mathcal{B}$. The aim of TR scheme is to compute the optimal $c(t)$ that reduces the PAPR of $x(t)$.

The PAPR reduction feature for DVB-T2 standard is optional. Around 1 % of the subcarriers are dedicated for PAPR reduction. The number of reserved tones for different OFDM symbol sizes is given in Table I. The PRT locations are specified by the DVB-T2 and ATSC3.0 standards.

Two different PAPR reduction methods have been adopted for the DVB-T2 and ATSC3.0 transmissions, one of which is a TR based method. The DVB-T2 TR algorithm suggested in [2] is very much similar to that one suggested in ATSC3.0. This algorithm is based on a gradient method that was first proposed in [1]. It involves in iteratively canceling out the highest peaks of the time domain signal, by a set of impulse-like signals, using PRTs. However, this gradient-based TR algorithm does not offer enough PAPR reduction performance even for a high number of iterations.

E. Power control

When activated, the power allocated to each PAPR pilot changes at each iteration. Hence, a power control (PC) scheme is included to verify the power spectrum mask of the DVB-T2 standard. In order to respect the DVB-T2 spectrum mask requirements, an iterative process should be implemented at the transmitter with a special need for a smooth control of the transmitted power on the dedicated subcarriers. To meet the DVB-T2 requirements, the power of reserved subcarriers should not exceed more than 10 dB w.r.t. the data subcarriers power.

$$\max_k |C_k|^2 \leq 10(A_{data})^2, \tag{9}$$

where A_{data} are the square root of the maximum available power per data subcarrier.

III. PAPR Reduction using new kernel definition

The techniques presented in this section uses a new kernel definition and allocates power to the subcarriers individually in order to maximize the power used for PAPR reduction. We discuss ICMP reduction technique [4] and propose a novel technique termed as GICMP.

A. New kernel definition based on individual reserved carrier

Instead of a Dirac-type kernel as suggested by DVB-T2, we aim at generating a comb-like one, for each reserved subcarrier. By phase-shifting the kernel, we try to reduce the peaks of the data signal. This kernel at each iteration i is defined as below

$$C^{(i)}[k] = \begin{cases} A_{max}, & k \in \mathcal{B} \\ 0, & else \end{cases} \tag{10}$$

where A_{max} is square root of the maximum power per PRT. In time domain, the new kernel is denoted as $c^{(i)}(kt/N)$. The real-time generation of kernels in ICMP only requires a simple phase shift operation.

B. The ICMP solution

The main idea behind the ICMP technique is to target multiple peaks in one iteration. In ICMP, the maximum number of iterations equals to the number of available subcarriers (R). In frequency-domain, the kernel amplitude is set to the power constraint A_{max} as per (10). It means no explicit power control is required at each iteration with ICMP approach since the power constraint is respected by design.

1) Optimization condition: With ICMP, the optimal phase is identified such that S multiple peaks are reduced in a single iteration. Mathematically, the ICMP optimization problem can be stated as

$$\min_{\phi} \sum_{s \in H} \left| d_s(t) + c_s(t).e^{-j\phi} \right|^2, \tag{11}$$

where H is the set of the S highest peak positions of $d(t)$. Then, $d_s(t)$ and $c_s(t)$ represent the samples at corresponding to these positions for the data signal and the adding kernel. The problem stated in (11) means, instead of reducing the peaks, we aim at reducing the energy above a particular threshold. By varying the size of S, we indirectly vary this threshold. So, a high value of S implies severe clipping leading to more PAPR reduction.

2) Optimal phase calculation: To solve (11), first, S highest peaks are identified. Then, the optimal phase ϕ has to be computed, which minimizes the sum of the squares of these peaks as follows

$$F(\phi) = \sum_{s \in H} \left| d_s(t) + c_s(t).e^{-j\phi} \right|^2, \tag{12}$$

By differentiating (12) and solving $\frac{\partial F}{\partial \phi} = 0$, to study the variation of $\frac{\partial F}{\partial \phi}$, we can find the optimal phase calculation. The computational complexity of H is $\mathcal{O}(N)$.

3) Latency: In ICMP, each iteration performs one peak search, every peak search traverses the whole signal. It means, the number of iterations executed by ICMP is equal to the number of available reserved subcarriers. So, lower modes in DVB-T2 such as 2K, 4K and 8K would not be a problem. Nevertheless, for higher modes of DVB-T2 and ATSC 3.0 such as 16K and 32K, where 144 and 288 subcarriers are reserved, it becomes increasingly challenging as induced latency is very large.

C. The GICMP solution

For higher modes of DVB-T2 and ATSC3.0 such as 16K and 32K, around 144 and 288 subcarriers are reserved respectively. Each iteration performs one peak search, every peak search traverses the whole signal. With 144 and 288 iterations the delay induced is enormous in ICMP. The resulting latency according to the number of PRTs may exceed the duration of one OFDM symbol depending on the used over clock factor. To address this latency issue, we propose a novel GICMP algorithm. It is achieved by dividing the reserved pilots into G groups as below

$$\mathcal{B} = \{\mathcal{B}_1, \dots, \mathcal{B}_G\}, \tag{13}$$

$$\mathcal{B}_i = \{P_{1+\frac{(i-1)R}{G}}, \dots, P_{1+\frac{iR}{G}}\}, \text{ for } 1 \le i \le G. \tag{14}$$

Then, only one peak search is executed per group. Apart from this, the remaining steps of the algorithm, i.e. the optimization condition and optimal phase calculation remains unchanged. As these steps are now uncorrelated and if needed, can be executed in parallel to further reduce the latency. The principle of GICMP is illustrated in Fig. 2. The GICMP algorithm is explained below.

Step 1: Firstly, we generate complex symbol vector D and then put zeros in the PRT locations, for $0 \le k \le N-1$ as

$$D[k] = \begin{cases} data, & k \in \mathcal{B}^c \\ 0, & k \in \mathcal{B} \end{cases} \tag{15}$$

Step 2: The OFDM data symbol $d(t)$ is obtained by OFDM modulation of the DT set D as per (1). Then, the OFDM symbol is initialized with the data symbol as shown below,

$$x(t) = d(t). \tag{16}$$

where $d(t) \neq 0$, for $t = [0, T)$.

Step 3: The total PRTs are partitioned into G groups and the group counter is initialized to $i = 1$.

Step 4: If $i \le G$, find S highest peaks of $x(t)$ and the PRT counter is initialized to $k = 1$. Else goto **Step 10**.

Step 5: If $k \le \frac{R}{G}$, compute the kernel $c^{(i)}(kt/N)$ by phase shifting. Else goto **Step 9**.

Step 6: Find the optimal phase ϕ of kernel as per (12).

Step 7: Once optimal phase ϕ is calculated, then add it to the information signal $x(t)$ as

$$x(t) = d(t) + c^{(i)}(kt/N)e^{j\phi_k}. \tag{17}$$

Step 8: Increment k by 1 and goto **Step 5**.

Step 9: Increment i by 1 and goto **Step 4**.

Step 10: Exit the algorithm.

Thus, in GICMP, the final peak cancellation $c(t)$ shall be the kernel $c_s(t)$ that is aimed at reducing S peaks, which can be written as

$$c(t) = c_s(t) = \sum_{i=1}^{G} \sum_{k=1}^{\frac{R}{G}} c^{(i)}(kt/N)e^{j\phi_k}. \tag{18}$$

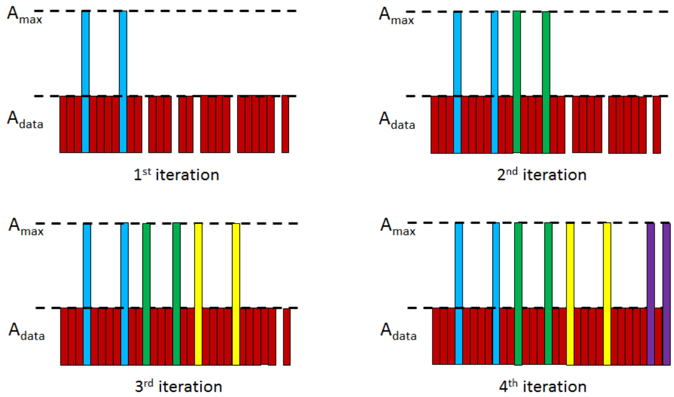

Fig. 2: Relation between the kernel definition and the iteration count in GICMP scheme in 4 groups for 2 subcarriers.

With classical ICMP, the number of iterations is equal to the total number of reserved subcarriers, while with GICMP it is equal to the number of groups. This explains the substantial decrease in latency. With ICMP, at the end of each iteration, we shall have peak reduction, which shall be considered as input data signal for the next iteration. With GICMP, due to parallelization involved in the implementation, the original data signal remains the same for all groups and the final peak cancellation signal is computed by adding the peak cancellation sub-signals from each parallel process.

IV. Simulation Results and Conclusion

A DVB-T2 system is simulated in 32K mode with 64 QAM constellation. The 32K mode is chosen because to the best of our knowledge, the preferred mode for the deployment of the terrestrial broadcast. The performance of the GICMP method with $S = 100$ and different number of groups $G = \{1, 2, 8\}$ is evaluated in the presence of NL PA. A Rapp model of PA with smoothing factor $p = 6$ is assumed. When comparing different methods, we assume same mode and same number of subcarriers reserved for PAPR reduction and same PC limitation (i.e. PC=10 dB). The PAPR reduction gain is evaluated in terms of IBO gain for aforementioned different system constraints.

The performance in terms of CCDF of PAPR is shown in Fig. 3. In the legend, "Original" indicates the original OFDM signal without any PAPR reduction, "Gradient-based TR" is the OFDM signal with TR method suggested in the DVB-T2 standard with 30 iterations, "GICMP (G=1, S=100)" refers to the OFDM signal with GICMP having one group aiming at reducing 100 peaks and vice-versa. The values at 10^{-3} of CCDF of PAPR in Fig. 3, has been summarized in Table II. We can notice that even though the gradient-based TR algorithm reduces the PAPR, it is outperformed by ICMP with S=100

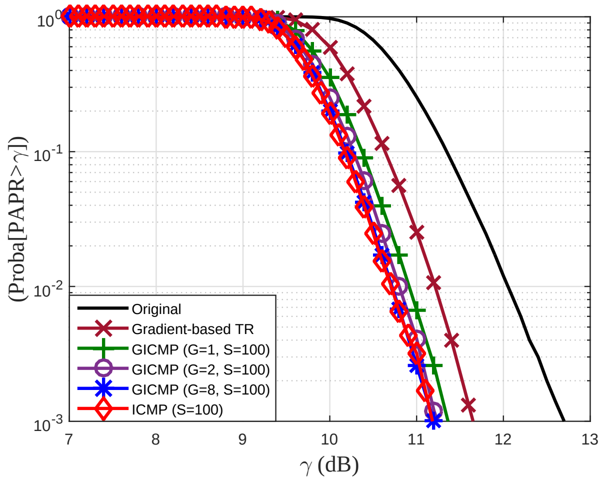

Fig. 3: CCDF for a DVB-T2 system in 32K mode with different TR methods for Rapp model of PA, $p = 6$ and PC=10 dB.

TABLE II: CCDFs of PAPR at 10^{-3} value.

Method	CCDF of PAPR at 10^{-3} (in dB)
Original‡	12.70
Gradient-based TR	11.65
GICMP, G=1, S=100	11.36
GICMP, G=2, S=100	11.24
GICMP, G=8, S=100	11.20
ICMP, S=100	11.18

‡: i.e. signal without any PAPR reduction

by around 0.47 dB at 10^{-3} of CCDF of PAPR. The CCDFs of GICMP with $G = \{2, 8\}$, S is 100 is almost identical to that of ICMP with $S = 100$. It is interesting to mention that varying G does not impact much the CCDF performance of GICMP. This is a direct implication of the new kernel definition. This validates the fact that the CCDF reflects only the statistics of the highest pick and is not influenced by additional peaks that are being reduced. So, it is necessary to analyze the performance in terms of MER.

The MER results are shown in Fig. 4. The IBO gain can be deducted by comparing the MER values of the signal with and without PAPR reduction. In popular practice, the target value of MER is 40 dB [8] and the IBO gains are summarized in Table III. In the figure it can be noticed that the GICMP, $G = 1$ outperforms the gradient-based TR method suggested in the DVB-T2 standard, both in terms of latency and IBO gain by 0.21 dB at 40 dB of MER. This translates into a huge reduction of processing delay for GICMP, since the peak detection process involves very high latency. Indeed, each new peak detection step can be launched only after the application of the kernel all along th OFDM symbol, which makes this step have strong influence on the total delay of any peak detection based PAPR reduction algorithm. As the G size increases, we can notice that GICMP offers more IBO gain as shown in Table III. For S=100, the GICMP algorithm with G=8, S=100 has almost the same performance as ICMP. To achieve this performance, the ICMP needs to make 288 iterations, while GICMP just needs 8. So, the GICMP algorithm with $G = 8$

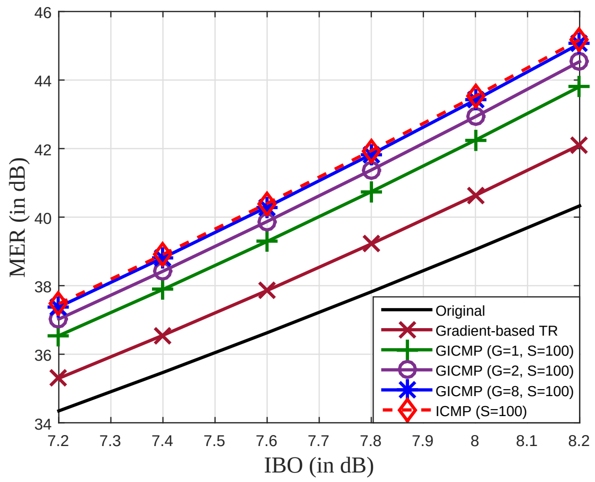

Fig. 4: MER for a DVB-T2 system in 32K mode with different TR methods for Rapp model of PA, $p = 6$ and PC=10 dB.

TABLE III: Relative IBO gains.

Method	Relative IBO gain at 40 dB of MER
Gradient-based TR	0.24 dB†
GICMP, G=1, S=100	0.45 dB†
GICMP, G=2, S=100	0.53 dB†
GICMP, G=8, S=100	0.59 dB†
ICMP, S=100	0.60 dB†

†: The original signal has an IBO of 8.15 dB

in 32K mode, leading to 8 iterations is then a solution which offers very good performance/latency trade-off.

V. Conclusion

The gradient-based TR method suggested in DVB-T2 and ATSC3.0 offers low PAPR reduction. The new kernel design proposed in this paper can be constructed through simple phase shift operations. The new GICMP method proposed in this paper deals with the latency issue in the higher modes of the two broadcasting standards. The simulation results show this PAPR reduction technique offers a very good performance/latency tradeoff for the implementation in future DVB-T2 and ATSC 3.0 transmitters.

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