

Research Article

Effects of Power Amplifier Nonlinearity on OTFS Signals

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Abstract

Orthogonal Time Frequency Space (OTFS) modulation has emerged as a leading candidate for 6G wireless systems due to its exceptional robustness against high mobility and frequency-selective fading channels. However, its multicarrier structure inherently generates a high Peak-to-Average Power Ratio (PAPR), making OTFS signals highly susceptible to nonlinear distortions introduced by High Power Amplifiers (HPAs). This paper investigates the impact of HPA nonlinearity on OTFS transmission in terrestrial radio environments, using the Rapp model to characterize amplifier behavior. We evaluate key performance metrics including PAPR, Complementary Cumulative Distribution Function (CCDF), Bit Error Rate (BER), Adjacent Channel Power Ratio (ACPR), and amplifier efficiency under varying Input Back-Off (IBO) values (0.5 dB to 4 dB). Our results demonstrate that OTFS exhibits a significantly higher PAPR than conventional 16-QAM, necessitating a larger IBO to avoid saturation. While increasing IBO improves linearity and reduces BER particularly in realistic Rayleigh fading channels it comes at the cost of drastically reduced amplifier efficiency, dropping from 70% at IBO = 0 dB to below 15% at IBO = 6 dB. Furthermore, nonlinear amplification severely degrades spectral purity: ACPR deteriorates from -37 dB (before amplification) to -15 dB (after amplification), indicating a 22 dB increase in out-of-band emissions and a substantial risk of interference with adjacent channels.

Keywords

HPA, PAPR, IBO, OTFS, BER, ACPR, Non-Linearity

1. Introduction

Wireless communication systems are undergoing rapid evolution, driven by increasing demands for data rate, mobility, reliability, and spectral efficiency. In this context, Orthogonal Time Frequency Space (OTFS) modulation has emerged as a promising technology for 6G networks, offering exceptional robustness against frequency and time-selective channels particularly in high-mobility environments. Unlike conventional multicarrier modulations such as OFDM (Orthogonal Frequency Division Multiplexing), OTFS operates in the delay-Doppler domain, enabling uniform signal energy distribution and enhanced resilience to fading. However,

despite its numerous advantages, the OTFS signal suffers from a major drawback: high Peak-to-Average Power Ratio (PAPR). This high PAPR makes the signal particularly sensitive to nonlinearities in High Power Amplifiers (HPA), which are essential components in any radio transmission chain. This paper aims to conduct a thorough analysis of the impact of power amplifier nonlinearities on OTFS signals, considering key parameters such as BER, ACPR, PAPR, and amplifier efficiency. A comparative study is performed across various IBO values using the Rapp amplifier model adapted for terrestrial radio transmissions. This paper makes several

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original and relevant contributions to the field of wireless communications. It investigates the effects of distortion introduced by nonlinear High Power Amplifiers (HPAs) from multiple perspectives. Rather than relying on a single performance metric, the study proposes a multidimensional evaluation that integrates: PAPR, BER over realistic channel conditions (AWGN and Rayleigh), spectral purity via ACPR, and amplifier power efficiency. A key finding of the paper is the demonstration that preserving performance i.e., achieving a BER close to the ideal case requires a high Input Back-Off (IBO), which in turn leads to a drastic reduction in amplifier efficiency. Furthermore, the paper shows that nonlinear distortion severely degrades spectral purity, significantly worsening the ACPR. This result highlights a substantial risk of inter-channel interference that must be accounted for in OTFS-based systems and underscores the necessity of corrective techniques such as digital predistortion for practical deployment. These contributions provide valuable insights for engineers and researchers working on the design, evaluation, and standardization of future 6G wireless communication systems.

2. Literature Review

Orthogonal Time Frequency Space (OTFS) modulation has attracted growing interest as a leading candidate for future 6G wireless networks due to its exceptional robustness in high-mobility environments and in the presence of frequency-selective fading. While numerous studies have investigated OTFS from the perspectives of channel estimation, equalization, and receiver-side detection, only a few have addressed the impact of real-world transmitter impairments particularly the nonlinear distortion introduced by High Power Amplifiers (HPAs).

It is worth noting that extensive research exists on the effects of HPA nonlinearity on traditional waveforms such as OFDM. In contrast, studies focusing on OTFS modulation remain very limited. A few recent works have started exploring HPA behavior when amplifying OTFS signals, but they typically focus exclusively on Bit Error Rate (BER) for example, as in [16]. Other studies, such as [17], propose PAPR reduction techniques for OTFS signals without examining the impact of nonlinearity on amplifier power efficiency.

Notably, no published work to date provides a comprehensive, multi-dimensional evaluation of HPA nonlinearity on OTFS signals that jointly considers BER, Adjacent Channel Power Ratio (ACPR), Input Back-Off (IBO), and amplifier efficiency.

These gaps are critical: although OTFS promises out-

standing reliability in theory, its practical deployment hinges on its ability to coexist with real hardware limitations especially those imposed by nonlinear power amplification. The findings presented in this paper assist 6G system designers in delivering users a reliable network with low energy consumption.

3. Research Methodology

This study aims to analyze the impact of power amplifier nonlinearities on OTFS-modulated signals in the context of terrestrial radio communications. The adopted methodology is based on a simulation-driven approach that combines OTFS signal modeling, nonlinear amplifier characterization using the Rapp model, and quantitative evaluation of several key performance metrics. The following steps were carried out:

Step 1: Initialization of simulation parameters

Step 2: Generation of information bits

Step 3: OTFS modulation

Step 4: Signal amplification

Step 5: OTFS demodulation

Step 6: Performance metric evaluation

This methodology clearly identifies the trade-offs among signal quality, spectral integrity, and power efficiency in OTFS systems subjected to high-power amplifier distortions, and provides a solid foundation for the development of future corrective solutions (e.g., digital predistortion, PAPR reduction techniques, etc.).

4. Operating Principle of Power Amplifiers

In telecommunications systems, the signal after undergoing various stages of coding, modulation, and upconversion to the carrier frequency is amplified to withstand the attenuation caused by free-space propagation. A High Power Amplifier (HPA) is therefore an electronic device that converts an input signal into an output signal with significantly higher power.

4.1. AM/AM (Amplitude/Amplitude) and AM/PM (Amplitude/Phase) Transfer Characteristics of a Power Amplifier

The curve showing the variation of output power as a function of input power of a power amplifier is also referred to as the AM/AM characteristic. It exhibits a typical shape for all amplifiers (see Figure 1).

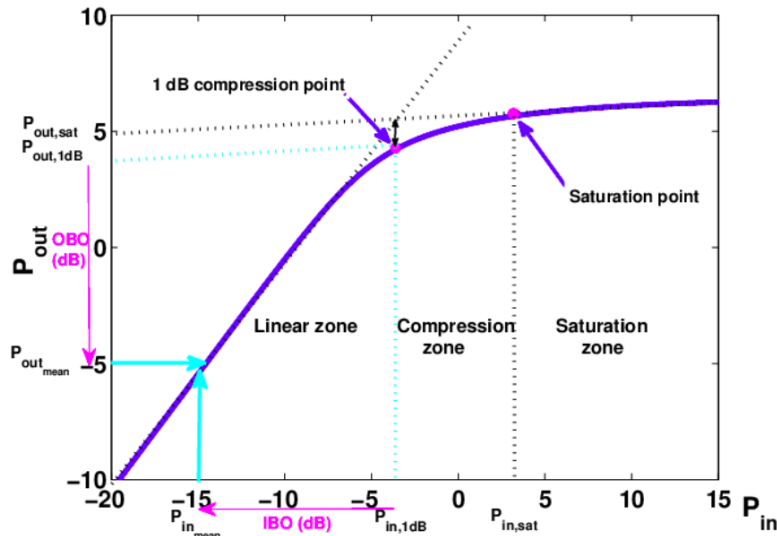


Figure 1. AM/AM characteristics.

The AM/AM characteristic of a power amplifier is divided into three regions [1-10]:

Linear zone: In this region, the amplifier exhibits linear behavior. The output power is proportional to the input power, with the proportionality factor known as the amplifier gain. Input power levels are low. In this region, distortions caused by nonlinearity are nonexistent. When operating with sufficient back-off to avoid distortions, the amplifier functions within this linear region.

Compression zone: In this region, output power is no longer proportional to input power. The curve begins to bend, marking the onset of nonlinear behavior. Signal distortions appear and become increasingly significant as input power rises. The amplifier gain decreases for high input power levels, which is why this region is referred to as the gain compression region. The 1-dB gain compression point lies within this region; it is defined as the point where the difference between the actual gain curve and the ideal linear gain equals 1 dB. This point is a key characteristic of the power amplifier.

Saturation zone: In this region, the output power remains nearly constant regardless of further increases in input power. This constant output power level is referred to as the saturation power, which is another fundamental characteristic of the power amplifier.

The curve showing phase shift as a function of input amplitude is called the AM/PM transfer characteristic. It has no standard shape; it varies depending on the amplifier's design technique and operating conditions.

In short, amplification is a nonlinear operation characterized by amplitude compression (AM/AM) and phase shift at the output (AM/PM).

4.2. Amplifier Efficiency

A power amplifier is an energy converting device featuring two inputs: the power supply and the signal to be amplified

and one output for the amplified signal.

The amplifier's power supply delivers a total DC power P_{dc} , which ideally should be entirely converted into useful output signal power P_s , with no conversion losses. Unfortunately, in practice, a portion of the input power is inevitably lost as dissipated power P_{diss} within the amplifier (Figure 2).

Power efficiency expresses the ratio between the output power and the power supplied by the power source. This parameter provides information about the amplifier's power consumption. It is given by Equation (1):

$$\eta_{DC} = \frac{P_s}{P_{dc}} \quad (1)$$

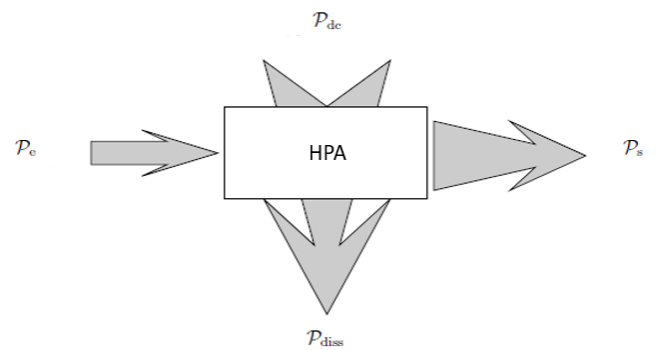


Figure 2. The various power components of a power amplifier.

4.3. Input Back-Off and Output Back-Off

To avoid or at least mitigate the detrimental effects caused by amplifier nonlinearity, the amplifier is often oversized i.e., operated with a certain amount of back-off to ensure operation within or near the linear region. This back-off is typically referenced either to the 1-dB compression point or to the saturation power level. The resulting parameters are known as Input Back-Off (IBO) and Output Back-Off (OBO), which are

useful for quantifying the degree of amplifier oversizing.

Let P_e denote the input signal power and P_s the corresponding output power, $P_{s,1dB}$ the output power at the 1-dB compression point and $P_{e,1dB}$ the corresponding input power, and $P_{s,sat}$ the output power at saturation with $P_{e,sat}$ the corresponding input power.

Input Back-Off (IBO), typically expressed in dB, is the ratio between the input-referred saturation power $P_{e,sat}$ and the actual input signal power P_e , or alternatively, the ratio between the input power at the 1-dB compression point $P_{e,1dB}$ and the actual input signal power P_e .

$$IBO = 10 \log \frac{P_{e,sat}}{P_e} = P_{e,sat}(dB) - P_e(dB) \quad (2)$$

$$IBO = 10 \log \frac{P_{e,1dB}}{P_e} = P_{e,1dB}(dB) - P_e(dB) \quad (3)$$

Output Back-Off (OBO) is the ratio between the saturation output power $P_{s,sat}$ and the actual output signal power P_s , or alternatively, the ratio between the output power at the 1-dB compression point $P_{s,1dB}$ and the actual output signal power P_s .

$$OBO = 10 \log \frac{P_{s,sat}}{P_s} = P_{s,sat}(dB) - P_s(dB) \quad (4)$$

$$OBO = 10 \log \frac{P_{s,1dB}}{P_s} = P_{s,1dB}(dB) - P_s(dB) \quad (5)$$

4.4. Mathematical Modeling of Power Amplifier

In this article, we will discuss and use memoryless models of amplifiers.

The input-output relationship of a power amplifier is given by Equation (6):

$$y(t) = F[x(t)] \quad (6)$$

where $F[\]$ is a nonlinear function, $x(t)$ is the input signal to the amplifier, and $y(t)$ is the output signal.

As previously mentioned, nonlinear amplification of a signal affects both its magnitude and phase. Therefore, the output signal of the power amplifier can also be expressed as:

$$y(t) = F_A[A(t)] \cdot e^{j(F_\phi[A(t)] + \varphi(t))} \quad (7)$$

where $A(t)$ and $\varphi(t)$ are the amplitude and phase of the signal $x(t)$, respectively; $F_A[A(t)]$ describes the AM/AM transfer characteristic (amplitude distortion), and $F_\phi[A(t)]$ describes the AM/PM transfer characteristic (phase distortion) of the amplifier [1-10].

Polynomial model

For the polynomial model, $F_A[A(t)]$ and $F_\phi[A(t)]$ are given by:

$$F_A[A(t)] = \sum_{m=0}^{N-1} \frac{a_{2m+1}}{2^{2m}} \binom{2m+1}{m+1} [A(t)]^{2m+1} \quad (8)$$

$$F_\phi[A(t)] = 0 \quad (9)$$

The polynomial model is the simplest model for nonlinear behavior of a power amplifier.

Rapp model

The Rapp model is used to model solid-state power amplifiers (SSPAs) employed in terrestrial radio transmissions. For this model, the AM/AM and AM/PM transfer characteristics are expressed as:

$$F_A[A(t)] = \frac{G_{PA} A(t)}{\left[1 + \left(\frac{G_{PA} A(t)}{A_{sat}}\right)^{2p}\right]^{\frac{1}{2p}}} \quad (10)$$

$$F_\phi[A(t)] = 0 \quad (11)$$

p is an integer often referred to as the "knee factor", it controls the smoothness of the transition between the linear region and the saturation region of the amplifier's AM/AM transfer characteristic. G_{PA} is the amplifier gain in the linear region, and A_{sat} is the saturation amplitude.

Saleh model

The Saleh model characterizes traveling-wave tube amplifiers (TWTAs) used in satellite communications. For this model, the AM/AM and AM/PM transfer characteristics are expressed as follows:

$$F_A[A(t)] = \frac{\alpha_a [A(t)]}{1 + \beta_a [A(t)]^2} \quad (12)$$

$$F_\phi[A(t)] = \frac{\alpha_\phi [A(t)]^2}{1 + \beta_\phi [A(t)]^2} \quad (13)$$

Where $\alpha_a = 1.9638$, $\beta_a = 0.9945$, $\alpha_\phi = 2.5293$, $\beta_\phi = 2.8168$. These values were obtained from experimental measurements in a multi-carrier transmission scenario.

5. OTFS Modulation

5.1. Fading

The transmitted signal therefore undergoes reflections, refractions, diffractions, and scattering during propagation through the channel. Consequently, the receiver captures a series of echoes arriving from various paths. These echoes can combine constructively or destructively at the receiver, leading to signal fading (or attenuation). The impulse response of the multipath channel, denoted $h(t)$, is given by Equation (14):

$$h(t) = \sum_{i=0}^{M-1} h_i \cdot \delta(t - \tau_i) \cdot e^{j\theta_i} \quad (14)$$

Where:

M : number of multipath

h_i : channel gains for the individual paths

τ_i : the respective delays of each path

$\delta(t)$: Dirac impulse

θ_i : phases associated with each path.

Denoting τ_{max} as the maximum delay beyond which the channel gains h_i along the various paths become very small, we obtain a condition that helps minimize inter-symbol interference (ISI) (Equation (15)):

$$T_s \gg \tau_{max} \quad (15)$$

Where T_s is the symbol duration.

5.2. Coherence Bandwidth

By transitioning to the frequency domain, one can define

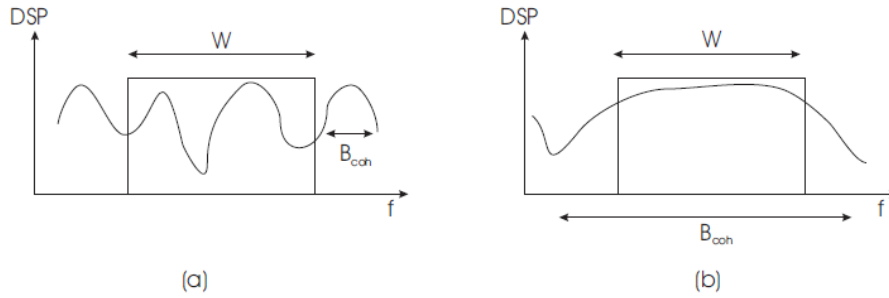


Figure 3. Frequency selectivity of the transmission channel (a: frequency-selective channel, b: non-frequency-selective channel).

5.4. Principle of OTFS Modulation

Multicarrier modulation aims to mitigate the effects of frequency selectivity of the channel, thereby achieving a locally flat channel response at the level of each subcarrier.

OTFS (Orthogonal Time Frequency Space) is widely regarded as one of the key technologies for 6G networks, particularly to meet extreme requirements in terms of mobility, reliability, ultra-low latency, and spectral efficiency [11-15].

Figure 4 illustrates the principle of OTFS modulation.

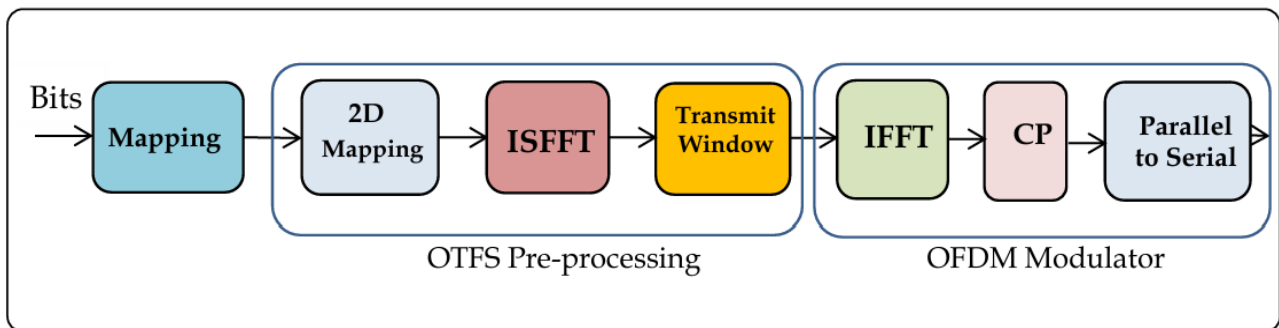


Figure 4. OTFS modulation.

Step 1: Mapping

Conversion of bits into complex symbols using sin-

gle-carrier modulation QPSK, 16-QAM,

Step 2: 2D Mapping in the Delay-Doppler Domain

The complex symbols are placed on a 2D grid:

- 1) Horizontal axis: delay index l (temporal delay)
- 2) Vertical axis: Doppler index k (frequency shift)

Data is organized in the delay–Doppler domain, not in the time or frequency domain.

Step 3: ISFFT (Inverse Symplectic Finite Fourier Transform)

This transformation converts the symbols $x[k, l]$ from the delay–Doppler domain into the time–frequency domain $X[n, m]$.

$$X[n, m] = \frac{1}{\sqrt{MN}} \sum_{l=0}^{M-1} \sum_{k=0}^{N-1} x[k, l] e^{j2\pi(\frac{nk}{N} - \frac{ml}{M})} \quad (17)$$

Step 4: Transmit Window

Filter the signal to reduce sidelobes and inter-symbol interference (ISI).

Step 5: IFFT (Inverse Fast Fourier Transform)

OFDM modulation

Step 6: CP (Cyclic Prefix)

Append a copy of the beginning of the symbol to its end. This is a standard technique in an OFDM system, which prevents inter-symbol interference.

Step 7: Parallel to Serial

The time-domain samples are serialized to form a continuous time signal.

Figure 5 illustrates the principle of OTFS demodulation.

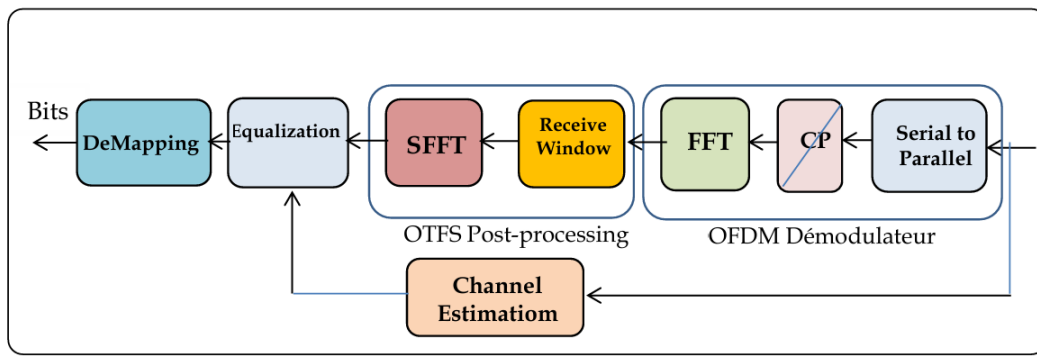


Figure 5. OTFS demodulation

Step 1: Serial to Parallel

Conversion of the serial stream into parallel.

Step 2: Removal of the Cyclic Prefix

The cyclic prefix, which was added at transmission to avoid inter-symbol interference, is removed here.

Step 3: FFT (Fast Fourier Transform)

Converts the time-domain signal into the frequency domain.

Step 4: Receive Window

Filtering to reduce spectral leakage and smooth transitions between symbols.

Step 5: SFFT (Symplectic Finite Fourier Transform)

Converts the data from the time–frequency domain $Y[n, m]$ into the delay–Doppler domain $y[k, l]$.

Step 6: Channel Estimation

Channel estimation is performed using pilot symbols inserted at transmitter. A pilot symbol is a symbol known in advance by both the transmitter and the receiver. By comparing the transmitted and received symbols, the channel state can be estimated.

Step 7: Equalization

Using the channel estimate obtained in the previous step,

the effects of the channel on the received symbols can be compensated.

Step 8: DeMapping

Conversion of the estimated complex symbols into binary bits using QPSK, QAM, ... demodulation.

6. Amplification of OTFS Signal

6.1. Simulation Parameters

Here are the parameters used in the simulation:

- 1) Modulation: OTFS
- 2) Mapping: 16-QAM
- 3) Number of subcarriers in frequency domain (N): 16
- 4) Number of subcarriers in time domain (M): 16
- 5) SNR (Signal-to-Noise Ratio): 0 dB – 20dB
- 6) IBO: 0.5dB, 1.5dB, 3dB, 4dB
- 7) Amplifier model: Rapp model because we are in a terrestrial radio transmission context
- 8) AM/AM characteristics of a power amplifier:

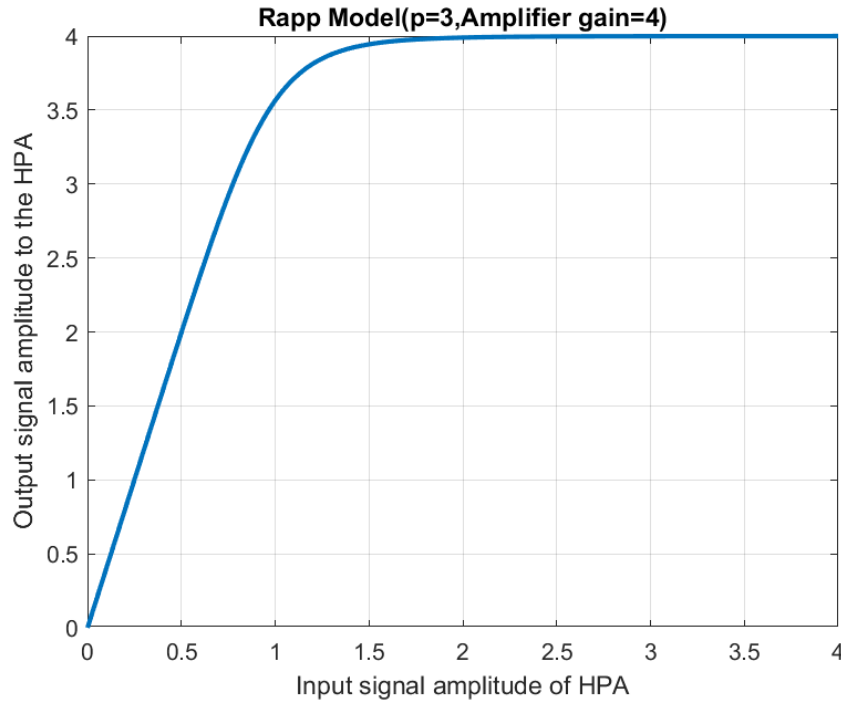


Figure 6. AM/AM characteristics of a power amplifier.

$A_{sat} = 4$: This value corresponds to a realistic saturation amplitude within the operating range of many modern RF power amplifiers based on GaN or Si LDMOS technologies commonly used in telecommunications. It enables the simulation of a realistic amplification scenario.

$G_{PA} = 4$: This gain is consistent with the typical characteristics of power amplifier stages operating in C-band or S-band, which are widely used in wireless infrastructure (e.g., 5G/6G base stations). Such a gain level ensures sufficient amplification while remaining compatible with the input power levels of modern modems.

$p = 3$: This parameter controls the smoothness of the transition between the linear region and the saturation region of the amplifier. A value of 3 represents a gradual yet realistic transition, reflecting the behavior of contemporary solid-state power amplifiers.

- 1) Programming environment: MATLAB 2023
- 2) Hardware specifications: CPU: Intel(R) Core i7-9750H, GPU: NVIDIA GeForce RTX 2060, RAM: 16Go

6.2. Metrics for Measuring Amplifier Nonlinearity

BER (Bit Error Rate):

It is a key performance metric in digital communication systems that measures the number of erroneous bits received divided by the total number of bits transmitted.

CCDF (Complementary Cumulative Distribution Function) of PAPR (Peak-to-Average Power Ratio):

Equation (18) provides the general expression for the PAPR. This parameter is defined as the ratio between the peak

power (P_{max}) and the average power (P_{moy}) of the signal $S(t)$ over a time interval T :

$$PAPR = \frac{P_{max}}{P_{moy}} = \frac{\max_{t \in [0, T]} |S(t)|^2}{\frac{1}{T} \int_0^T |S(t)|^2 dt} \quad (18)$$

A high PAPR indicates that the signal exhibits large amplitude variations.

To evaluate the PAPR, the CCDF is used. This function gives the probability that the PAPR exceeds a threshold value ψ , and is expressed by Equation (19).

$$CCDF(\psi) = \Pr [PAPR \geq \psi] \quad (19)$$

The slower the CCDF decreases, the higher the probability that the signal has a high PAPR.

ACPR (Adjacent Channel Power Ratio):

It is the ratio of the power that a communication system transmits into the adjacent frequency channels to the power that it transmits into the main frequency channel.

$$ACPR = \frac{\text{Power in adjacent channel}}{\text{Power in main channel}} \quad (20)$$

ACPR is an important parameter that is used to ensure that a communication system does not interfere with the other systems operating in the nearby frequency bands. If the ACPR is low, the risk of interference with adjacent channels is low.

Amplifier efficiency

This metric has already been explained in Section 2.2.

6.3. Results

1) Comparison of the CCDF between a single-carrier (16-QAM) signal and a multi-carrier (OTFS) signal

From Figure 7, we deduce that the OTFS signal (multi-carrier) has a higher probability of exhibiting a high PAPR than the 16-QAM signal (single-carrier). A high PAPR re-

quires a larger back-off (IBO or OBO) in power amplifiers to avoid saturation and signal distortion. Although OTFS is designed to be robust against frequency- and time-selective channels, its multi-carrier structure tends to generate signals with a wider amplitude distribution, resulting in a higher PAPR.

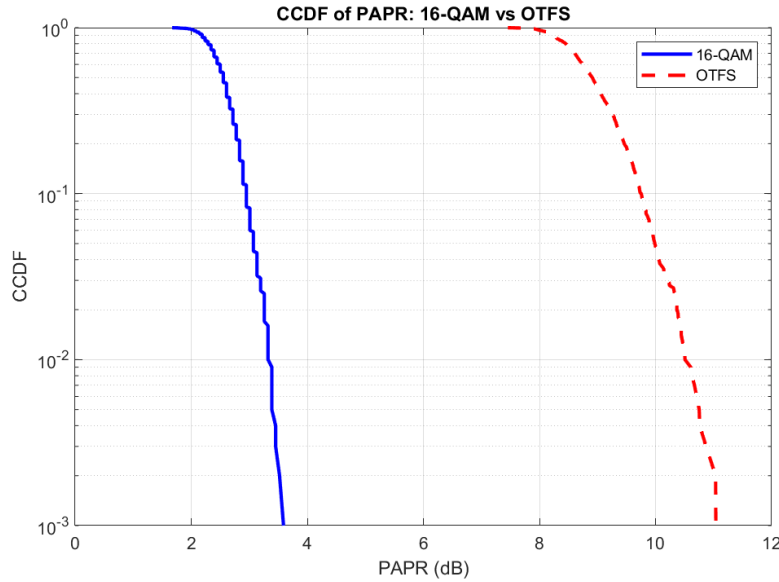


Figure 7. CCDF of PAPR: 16-QAM vs OTFS.

2) Influence of IBO on the operation of the power amplifier

Figure 8 shows the transfer characteristic of a power amplifier modeled according to the Rapp model, for different IBO values. It can be deduced that for a low IBO (0.5 dB), the amplifier exhibits nonlinear behavior. As the IBO increases, the amplifier becomes more linear. For an IBO of 4 dB, the

AM/AM transfer characteristic is nearly linear. According to the definition of IBO previously discussed, a low IBO means the amplifier operates in the saturation region, while a high IBO indicates operation in the linear region. The results presented in this figure clearly confirm this behavior of the power amplifier.

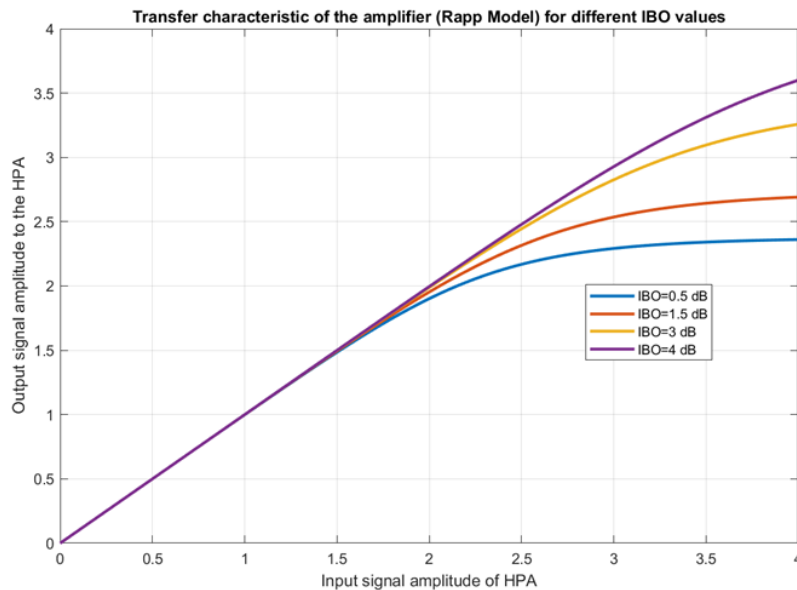


Figure 8. Influence of IBO on the operation of the power amplifier.

3) BER for linear amplification (ideal case), nonlinear amplification, and for different IBO values

We evaluated the BER over two channels:

- 1) AWGN (Additive White Gaussian Noise): This is an ideal noise model, additive and uniformly distributed across the entire frequency band. It serves as a reference for evaluating the performance of communication systems, particularly in terms of Bit Error Rate.

- 2) Rayleigh: This is a channel model in which there is no direct line-of-sight (NLOS) between the transmitter and receiver. In this channel, multiple propagation paths exist, each undergoing independent fading. It represents a realistic scenario for wireless communication environments.

Figures 9 and 10 show the BER of OTFS modulation for linear amplification (ideal case), nonlinear amplification, and for different IBO values.

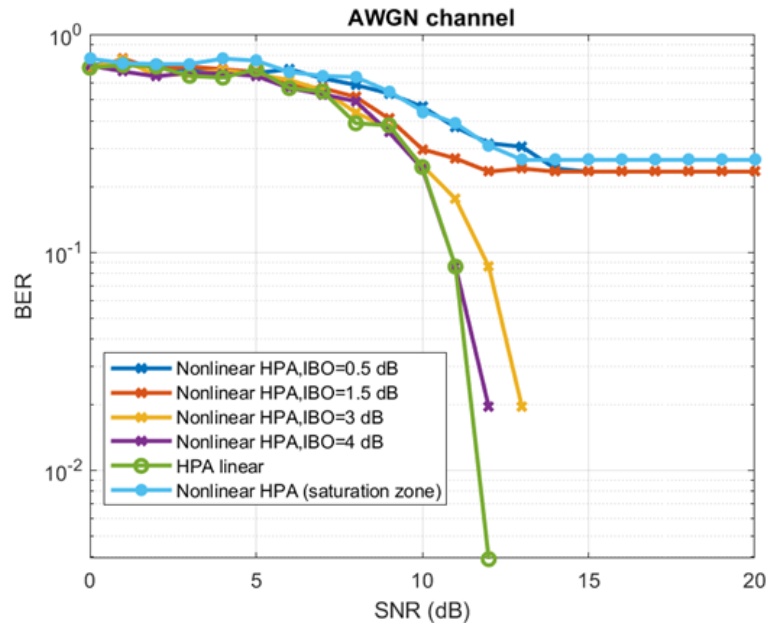


Figure 9. BER over AWGN Channel.

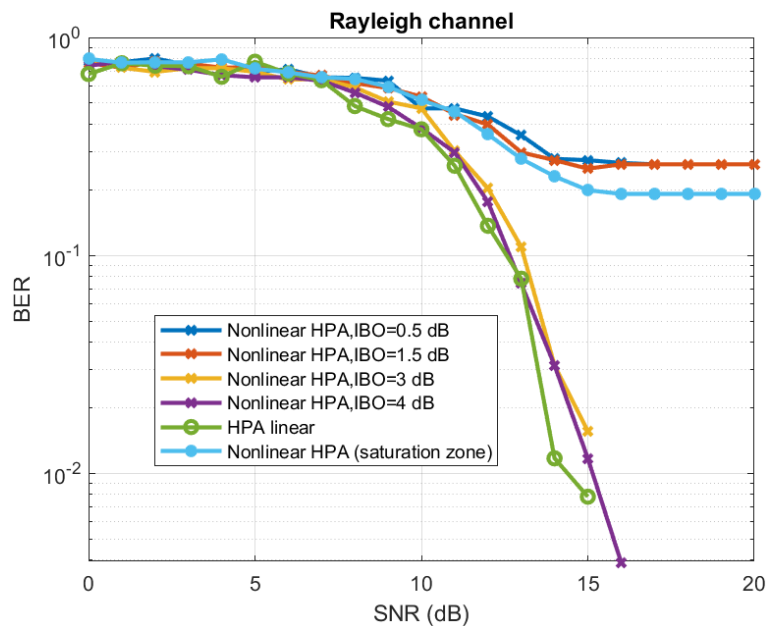


Figure 10. BER over Rayleigh Channel.

All curves exhibit a high BER at low SNR, followed by a rapid decrease as the SNR increases.

The BER after linear amplification (green curve) is the lowest, as it represents an ideal amplifier without nonlinear distortion.

The BER after nonlinear amplification (light blue curve) remains very high even at high SNR. Nonlinear amplification thus saturates the signal and causes significant information loss.

We also observe that a higher IBO significantly improves the BER: the higher the IBO, the closer the amplifier operates to its linear region.

4) Influence of IBO on amplifier efficiency

Figure 11 shows the evolution of amplifier efficiency as a function of IBO.

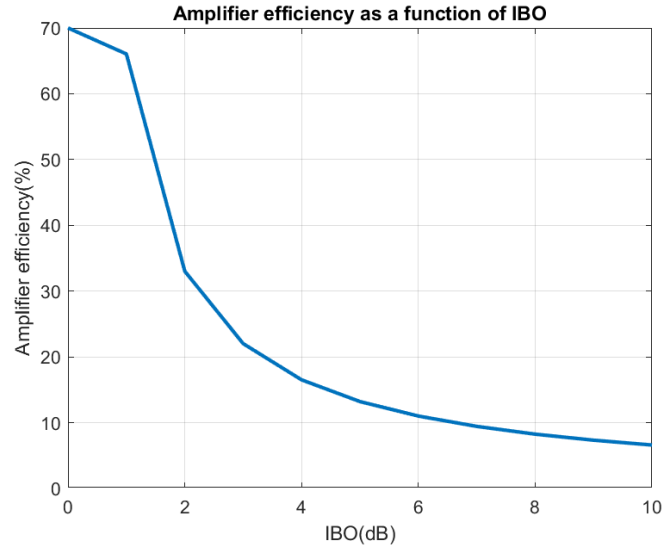


Figure 11. Amplifier efficiency as a function of IBO.

From this figure, we deduce that as the IBO increases, the amplifier efficiency decreases.

Between IBO = 0 dB and IBO = 2 dB, efficiency drops rapidly from 70% to 33%. This corresponds to the region where the amplifier begins to exit saturation, reducing distortion but at the cost of a significant loss in efficiency.

Between IBO = 2 dB and IBO = 6 dB, the amplifier effi-

ciency continues to decrease, but more gradually. We typically force the amplifier to operate in this range to achieve a good compromise between signal quality (low distortion) and acceptable efficiency (15–30%).

5) ACRP before and after HPA

Figure 12 shows us the Power Spectral Density (PSD) before and after amplification.

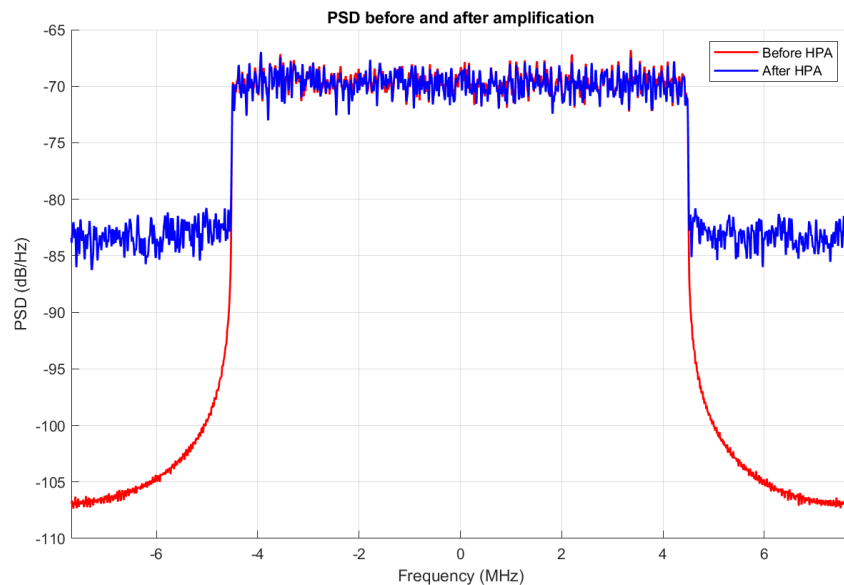


Figure 12. PSD before and after amplification.

From the PSD, we obtain the ACPR values given in Table 1.

Table 1. ACPR before and after amplification.

ACPR before HPA	ACPR after HPA
-37 dB	-15 dB

From these results, we deduce that the signal spectrum before amplification is well confined within the useful bandwidth (approximately ± 4 MHz). The side lobes decay rapidly. Indeed, the ACPR before amplification is -37 dB. We conclude that, prior to amplification, the signal spectrum is very clean, with minimal interference in adjacent channels.

After amplification, a significant increase in spectral noise is observed in the adjacent bands. Moreover, the shape of the spectrum within the main band is slightly distorted. The ACPR after amplification is -15 dB, meaning that the power in the adjacent channel has increased by 22 dB hence, the risk of interference with neighboring channels increases significantly.

7. Conclusion

This study has enabled a thorough analysis of the impact of power amplifier nonlinearities on OTFS modulation, a promising technology for future 6G wireless networks. The results demonstrate that, despite its exceptional robustness against frequency and time selective channels, the OTFS signal exhibits a high Peak-to-Average Power Ratio, rendering it particularly vulnerable to nonlinear distortions introduced by power amplifiers. The CCDF analysis of the PAPR confirmed that OTFS generates more frequent and higher power peaks than a single-carrier signal such as 16-QAM, necessitating a substantial Input Back-Off (IBO) to avoid amplifier saturation. Using the Rapp mode adapted for terrestrial radio transmissions the AM/AM characteristics of the amplifier were precisely characterized, revealing that increasing IBO significantly improves linearity at the cost of reduced power efficiency. Simulations conducted over AWGN and Rayleigh channels revealed that:

- 1) Without compensation, amplifier nonlinearity causes severe BER degradation, even at high SNR levels.
- 2) Insufficient IBO (≤ 0.5 dB) leads to massive signal saturation and significant information loss.
- 3) An IBO ≥ 3 -4 dB enables performance close to that of an ideal amplifier, but with a drastic drop in efficiency from 70% down to less than 15%.

Furthermore, spectral analysis showed significant adjacent-channel pollution following amplification, with the ACPR degrading from -37 dB before amplification to -15 dB after. This spectral degradation underscores the heightened

risk of interference in multi-user environments. In summary, this study highlights the fundamental trade-off between signal quality and energy efficiency in OTFS systems. To reconcile performance with efficiency, future research must explore solutions such as digital predistortion or PAPR reduction techniques. These approaches are essential to enable the practical integration of OTFS modulation into real-world communication systems, particularly those that are embedded or power-constrained. In summary, this paper does more than merely quantify a problem; it raises a clear warning about a major barrier to the industrial adoption of OTFS, while simultaneously outlining a concrete path toward practical solutions that can overcome its hardware-related limitations.

Abbreviations

6G	Sixth Generation of Mobile Communications
ACPR	Adjacent Channel Power Ratio
AM	Amplitude
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CCDF	Complementary Cumulative Distribution Function
CP	Cyclic Prefix
FFT	Fast Fourier Transform
HPA	High Power Amplifier
IBO	Input Back-Off
IFFT	Inverse Fast Fourier Transform
ISFFT	Inverse Symplectic Finite Fourier Transform
OBO	Output Back-Off
OFDM	Orthogonal Frequency Division Multiplexing
OTFS	Orthogonal Time Frequency Space
PAPR	Peak-to-Average Power Ratio
PM	Phase
QAM	Quadrature Amplitude Modulation
SFFT	Symplectic Finite Fourier Transform
SNR	Signal-to-Noise Ratio

Author Contributions

Hariniony Bienvenu Rakotonirina: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing – original draft, Writing – review & editing

Marie Emile Randrianandrasana: Supervision, Validation

Data Availability Statement

The datasets and code used for reconstruction are available upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

References

- [1] Li, W., Montoro, G., & Gilabert, P. L. (2025). Adaptive Digital Predistortion for User Equipment Power Amplifiers Under Dynamic Frequency, Bandwidth, and VSWR Variations. *IEEE Transactions on Microwave Theory and Techniques*, PP (99): 1-13. <https://doi.org/10.1109/TMTT.2025.3563159>
- [2] Wu, Y., Li, A., Beikmirza, M., Singh, G. D., Chen, Q., de Vreede, L. C. N., Alavi, M., & Gao, C. (2024). MP-DPD: Low-Complexity Mixed-Precision Neural Networks for En-ergy-Efficient Digital Predistortion of Wideband Power Amplifiers, *IEEE Microwave and Wireless Technology Letters*, <https://doi.org/10.1109/LMWT.2024.3386330>
- [3] Spano, C., Badini, D., Cazzella, L., & Matteucci, M. (2025). Local and Remote Digital Pre-Distortion for 5G Power Amplifiers with Safe Deep Reinforcement Learning. *Sensors*, 25(19), 6102. <https://doi.org/10.3390/s25196102>
- [4] Thys, C., Martinez Alonso, R., Lhomel, A., Fellmann, M., Deltimple, N., Rivet, F., & Pollin, S. (2024). Walsh-domain Neural Network for Power Amplifier Behavioral Modelling and Digital Predistortion. *IEEE International Symposium on Circuits and Systems (ISCAS)*, <https://doi.org/10.1109/ISCAS58744.2024.10557970>
- [5] Kostrzewska, K., & Kryszkiewicz, P. (2024). Power Amplifier Modeling Framework for Front-End-Aware Next-Generation Wireless Networks. *Electronics*, Mdpi. <https://doi.org/10.3390/electronics13091643>
- [6] Galaviz-Aguilar, J. A., Vargas-Rosales, C., Cárdenas-Valdez, J. R., Aguila-Torres, D. S., Flores-Hernández, L. (2022). A Comparison of Surrogate Behavioral Models for Power Amplifier Linearization under High Sparse Data. *Sensors*, 22(19), 7461. <https://doi.org/10.3390/s22197461>
- [7] Kang, M., Lim, S., Park, Y. (2023). Deep Neural Network for the Behavioral Modeling of Memory Effects and Supply Dependency on 10-W Nonlinear Power Amplifiers. *Journal of Electromagnetic Engineering and Science*, 23(2), 134-138. <https://doi.org/10.26866/jees.2023.2.r.152>
- [8] Ortali, J., Mons, S., Reveyard, T., Ngoya, E., & Mazière, C. (2025). Behavioral Modeling of RF Power Amplifiers Using a Time-Domain Characterization Approach. *International Journal of Microwave and Wireless Technologies*, 17(S6), 942-949. <https://doi.org/10.1017/S175907872500042X>
- [9] Tang, X., Wang, Z., Wang, Y. (2024). A Wideband Behavioral Model with Multiple States for RF Power Amplifier Based on Improved Recurrent Neural Network. 2024 2nd International Symposium of Electronics Design Automation (ISED A), <https://doi.org/10.1109/ISED A62518.2024.10617555>
- [10] Vimal, V., Thakur, P., Gupta, S., (2025). RF-Power Amplifier Modelling Using Inverse System Identification. *Discover Computing*, 28, 21. <https://doi.org/10.1007/s10791-025-09522-4>
- [11] Elakkiyachelvan, E., Kavitha, R., J., (2022). Space-Time Coding and LMMSE Receiver in OTFS Modulation. *Proc. ITSPWC 2022*. <https://doi.org/10.4108/cai.14-5-2022.2318877>
- [12] Sura H., Thamer M., Hassan F., (2025). A Performance and Evaluation of OTFS Modulation Systems Using Different High Mobility Channels. *Int. J. Electronics & Telecommunication*, 71(2), pp. 505-512. <https://doi.org/10.24425-ijet.2025.153598>
- [13] Obinna, O., Xutao, D., Agbotiname, L., Olamilekan, S., (2025). OTFS: A Potential Waveform for Space-Air-Ground Integrated Networks in 6G and Beyond. *Telecom*, 6(1), 19. <https://doi.org/10.3390/telecom6010019>
- [14] Franz, L., Hamdi, J., Alex, A., Frans, M. J., (2022). Orthogonal Time-Frequency Space Modulation Based on the Discrete Zak Transform. *Entropy*, 24(12), 1704. <https://doi.org/10.3390/e24121704>
- [15] Wei, L., Xuan, L., Jia, S., Lixin, L., Junfan, H., (2022). Underlying Security Transmission Design for OTFS Modulation. *Sensors*, 22(20), 7919. <https://doi.org/10.3390/s22207919>
- [16] S. Sharma, A. Singh, K. Deka and C. Adjih, (2023). Impact of Nonlinear Power Amplifier on BER Performance of OTFS Modulation. *IEEE International Conference on Advanced Networks and Telecommunications Systems (ANTS)*, pp. 627-632, <https://doi.org/10.1109/ANTS59832.2023.10469563>
- [17] Hossain, Sugiura, Md., Shimamura, Y., Ryu, T., Heung-Gyoon. (2020). DFT-Spread OTFS Communication System with the Reductions of PAPR and Nonlinear Degradation. *Wireless Personal Communications*. <https://doi.org/115.10.1007/s11277-020-07678-4>

Research Field

Hariniony Bienvenu Rakotonirina: Telecommunication, Signal processing, Compressive Sensing, Artificial intelligence, High Amplifier Power Nonlinearity

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