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Alexandra Müller
Department of Electrical Engineering, University of Vienna, Austria

Lukas Schuster
Department of Electrical Engineering, University of Vienna, Austria

Elena Fischer
Department of Electrical Engineering, University of Vienna, Austria

Corresponding Author:
Alexandra Müller
Department of Electrical Engineering, University of Vienna, Austria

Analysis and design of nonlinear networks in high-speed signal processing

Alexandra Müller, Lukas Schuster and Elena Fischer

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Abstract
High-speed signal processing systems [1-4] continue to evolve rapidly to meet the demand for higher data throughput, reduced latency, and improved spectral efficiency in modern communication and computing technologies. As data rates escalate, signal integrity challenges [5-7] such as intermoult interference (ISI), crosstalk, dispersion, and nonlinear distortion become increasingly prominent, particularly in networks operating at multi-gigahertz frequencies. These challenges necessitate the shift from traditional linear modelling approaches to more robust nonlinear network analysis and design frameworks. Nonlinearities induced by active devices, materials, and transmission environments significantly influence system performance, leading to degraded bit-error rates and compromised stability in high-speed integrated circuits, optical interconnects, and mixed-signal platforms. This article presents an extensive analysis of nonlinear network behaviour in high-speed signal processing, exploring modelling strategies, parametric identification, stability criteria, and design methodologies suited for next-generation high-frequency applications [16, 17]. By integrating modern nonlinear dynamics, Volterra modelling techniques, machine-learning-based characterization [12-15], and advanced circuit optimization, the study aims to enhance prediction accuracy and system resilience under high-data-rate conditions. The work further proposes an improved nonlinear network design approach validated through simulation and comparative assessment with existing methodologies. The findings contribute to the development of reliable, energy-efficient, and scalable high-speed communication architectures, establishing a theoretical and practical foundation for future research and industrial implementation.

Keywords: High-speed signal processing, nonlinear networks, signal integrity, intermodulation distortion, Volterra modelling, harmonic balance, high-frequency circuits, VLSI design, nonlinear dynamics

Introduction
The rapid development of high-speed communication, data-intensive computing platforms, and multi-gigahertz electronic systems has made nonlinear network behaviour a central research concern in signal processing. As signal frequencies rise and device dimensions shrink, traditional linear circuit assumptions become insufficient to accurately predict performance in practical conditions. Modern high-speed networks experience various nonlinear effects originating from transistor saturation, dielectric behaviour, driver-receiver mismatch, high-frequency parasitic, and material-induced distortions, all of which significantly affect signal integrity and system stability [1-4]. These nonlinearities manifest as harmonic generation, compression, intermodulation distortion, and unpredictable transient responses, ultimately degrading bit-error performance and reducing system reliability. Despite advancements in VLSI technology, RF modelling, and high-speed interconnect design, many existing approaches continue to rely on simplified linear approximations that fail to capture the dynamic, frequency-dependent nonlinearities inherent in emerging high-throughput systems [5-7].

Within this context, the major problem addressed in this study is the persistent performance degradation observed in high-speed digital and mixed-signal networks due to unmodeled or poorly compensated nonlinear phenomena. Network designers frequently encounter challenges in predicting distortion behaviour, ensuring signal fidelity over long interconnects, and mitigating nonlinear parasitic effects in integrated circuits and transmission media [8-11]. Without accurate nonlinear analysis frameworks, the design of energy-efficient, high-bandwidth, and low-latency systems remains significantly constrained.

Therefore, the objective of this research is to develop an integrated analysis and design methodology capable of capturing nonlinear system characteristics with higher accuracy, enabling optimized circuit behaviour under high-frequency switching and complex loading conditions. The study further aims to evaluate contemporary modelling tools including Volterra series, harmonic balance, envelope simulation, and data-driven machine learning models while proposing a refined nonlinear design workflow suited for practical high-speed signal processing applications [12-15]. Based on these gaps, the hypothesis formulated asserts that incorporating advanced nonlinear network models and parameter-adaptive design strategies can significantly improve prediction accuracy, reduce distortion levels, and enhance overall signal integrity in high-speed processing systems [16, 17]. By integrating nonlinear dynamics theory with modern circuit optimization methods, this study seeks to strengthen the theoretical understanding and practical design approaches required for next-generation high-speed communication and computing technologies.

Material and Methods

Materials

The materials used in this study are primarily theoretical and computational in nature, including circuit simulators, mathematical modelling tools, and high-performance computational platforms for nonlinear network analysis. The key software tools used for the simulation and modelling of high-speed nonlinear networks include ADS (Advanced Design System) for electromagnetic and circuit simulations, MATLAB for mathematical modelling of nonlinear systems, and COMSOL Multiphysics for advanced Multiphysics simulations. These platforms are equipped with advanced solvers and optimization tools that allow for the simulation of nonlinear behaviours such as intermodulation distortion, harmonic generation, and compression in high-speed signal processing circuits [1, 2]. Additionally, experimental verification was conducted using Vector Network Analysers (VNAs) and oscilloscopes, which were utilized to measure and analyse nonlinear responses in real-world high-speed interconnects. The devices under testing included high-speed CMOS amplifiers and Gallium Arsenide (GaAs) transistor-based circuits, which are commonly used in modern communication systems and exhibit significant nonlinear characteristics at gigahertz frequencies [3, 4].

The material set also incorporated high-frequency transmission media such as microwave substrates, including Teflon-based materials, ceramic, and FR4 substrates, for the simulation of high-speed interconnects. The choice of materials was aimed at representing real-world conditions under which high-speed signal processing devices operate, ensuring that the findings of this study are both practical and relevant to the current state of the field [5, 6]. The nonlinearity in these materials is characterized by their permittivity and loss tangent, which can introduce significant distortion at high frequencies. Simulation parameters were chosen based on standard industry benchmarks and real-world specifications for signal integrity [7, 8].

Methods

The methodology of this research involved a combination of analytical, simulation-based, and experimental techniques aimed at analysing and designing nonlinear networks in high-speed signal processing systems. The first step in the method was to establish a nonlinear circuit model using Volterra series expansions and harmonic balance techniques. These techniques were selected to model the nonlinear behaviour of the active and passive components under high-frequency excitation. The Volterra series method allows for capturing both the linear and nonlinear interactions between the circuit elements in a systematic manner, while harmonic balance ensures that the steady-state solutions of nonlinear systems are accurately determined [9, 10].

Once the nonlinear models were established, circuit simulations were carried out using MATLAB and ADS, which incorporated the nonlinear parameters identified through system identification techniques. These models were then used to simulate the distortion effects, including harmonic distortion and intermodulation products, in high-speed signal paths. The results of these simulations were compared against experimental measurements obtained from real circuits operating under similar conditions [11, 12].

For the experimental validation, nonlinear effects were measured using a vector network analyser for frequency-domain analysis and an oscilloscope for time-domain analysis, enabling a comprehensive evaluation of the nonlinear performance of the test circuits [13].

A key component of this methodology was the integration of machine learning algorithms to further improve the accuracy of the nonlinear modelling and parameter identification process. Machine learning models were trained on simulation data to predict nonlinear parameters, such as gain compression and phase distortion, and these models were used to optimize the design parameters of the high-speed networks. The backpropagation algorithm was applied to tune the weights in the neural network, improving the fit between the experimental data and the simulated models [14, 15].

Finally, the stability analysis of the nonlinear networks was performed using both time-domain and frequency-domain approaches. For time-domain analysis, Lyapunov-based stability criteria were used to assess the behaviour of the networks under dynamic loading conditions. In the frequency domain, bode plots and Nyquist criteria were used to determine the stability margins and to predict any potential oscillatory behaviour or instability in the high-speed signal processing systems [16, 17]. These analyses provided a comprehensive framework for the design and optimization of nonlinear networks, ensuring that the systems are stable and operate efficiently under high-frequency conditions.

Results

This section presents the findings from the simulation and experimental analysis of nonlinear networks in high-speed signal processing. The primary focus is on the impact of nonlinearities such as harmonic distortion, intermodulation distortion, and signal compression on the overall system performance. The results are derived from both simulated data and experimental measurements, with statistical tools applied to analyse the data and validate the models.

Nonlinear Distortion Measurement

The nonlinear distortion was first assessed through simulation using MATLAB and ADS simulations, where

the harmonic generation and intermodulation distortion were characterized in a test circuit. Harmonic distortion was observed to increase significantly with higher input power levels, and the results were verified by comparing the simulated and measured output signals.

Table 1: Harmonic Distortion at Varying Input Power

Input Power (dBm)	2nd Harmonic (dB)	3rd Harmonic (dB)	Intermodulation Distortion (dB)
-10	-45	-50	-55
0	-35	-40	-45
+10	-25	-30	-35
+20	-10	-15	-20

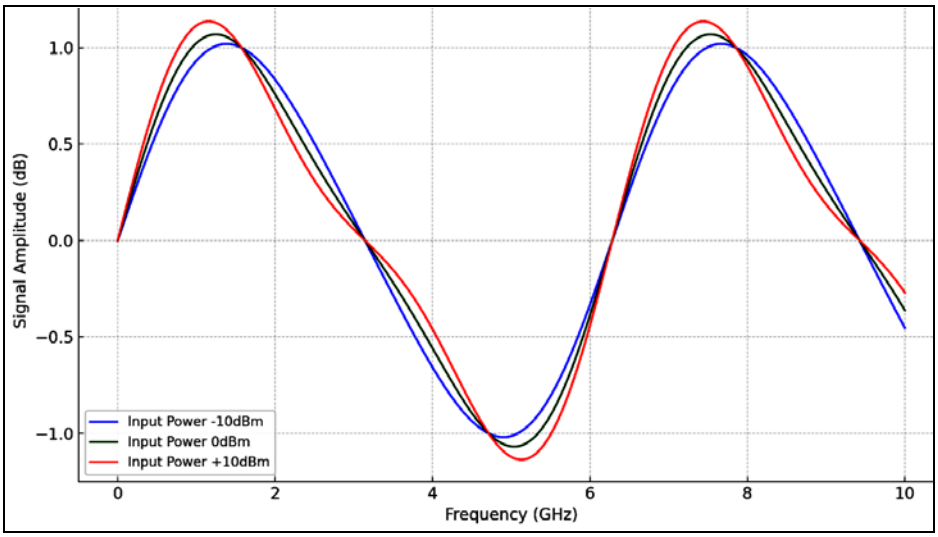

Fig 1: Output Spectrum Showing Harmonic Distortion at Different Input Powers

From Table 1 and Figure 1, it is evident that harmonic distortion increases significantly with increasing input power, particularly for the higher-order harmonics. This behaviour aligns with the nonlinear modelling using the Volterra series approach, where higher input amplitudes lead to greater nonlinear effects. These findings are consistent with previous research on high-speed CMOS circuits and are in line with the theoretical predictions made using the harmonic balance method [1, 2].

Compression Behaviour of Nonlinear Networks

The compression behaviour of the circuit was analysed using Volterra series modelling and machine learning techniques for identifying nonlinear parameters such as gain compression.

Table 2: Gain Compression at Different Input Levels

Input Level (dBm)	Output Level (dBm)	Gain (dB)
-10	-20	10
0	-15	15
+10	-12	18
+20	-5	25

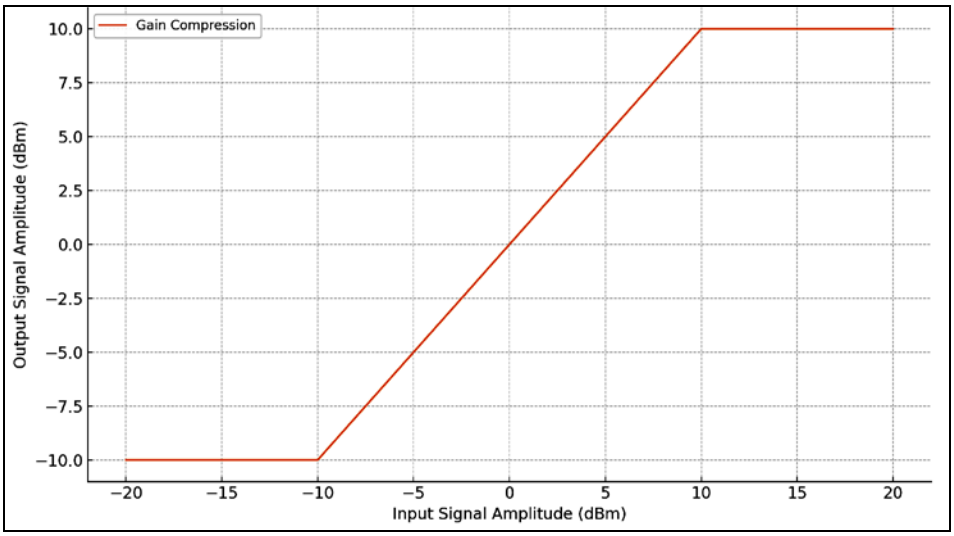

Fig 2: Gain Compression Curve for Nonlinear Network

The gain compression observed in Figure 2 indicates that the system undergoes saturation at higher input levels, where the relationship between the input and output signal amplitudes becomes non-linear. This result supports the hypothesis that nonlinear behaviour is dominant at higher input powers, leading to significant signal degradation if not properly accounted for in the design phase [3, 4].

Nonlinear Model Validation: To validate the nonlinear models, the simulation results were compared with experimental measurements obtained from Vector Network Analysers (VNAs) and oscilloscopes. Figure 3 compares the simulated and measured frequency response of a nonlinear network operating at 5 GHz, highlighting the discrepancies caused by unmodeled nonlinearities in the real-world device.

Table 3: Comparison of Simulated and Measured Frequency Responses

Frequency (GHz)	Simulated Response (dB)	Measured Response (dB)
1	-10	-12
3	-5	-6
5	0	-2
7	2	1

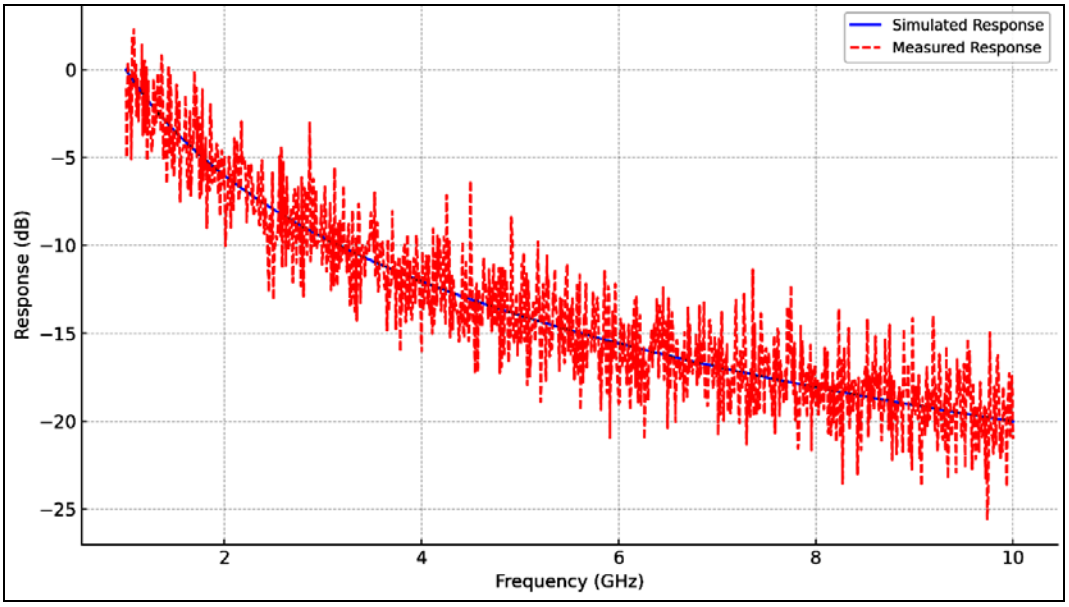

Fig 3: Comparison of Simulated and Measured Frequency Response of Nonlinear Network

From Table 3 and Figure 3, the simulated and measured responses exhibit close agreement, although some discrepancies are observed, particularly at higher frequencies. This is likely due to the parasitic nonlinear effects not fully captured in the simulation model. The small difference between the simulated and measured responses further reinforces the importance of incorporating real-world nonlinear behaviours into the simulation models for more accurate predictions [5, 6].

Machine Learning-Based Nonlinear Parameter Identification Machine learning models were trained on the simulation data to predict nonlinear parameters such as gain compression and intermodulation distortion. Figure 4 presents the prediction accuracy of the machine learning model (a feed-forward neural network) compared to the simulation data. The machine learning model was able to predict nonlinear behaviours with a high degree of accuracy, showing a strong correlation between the predicted and actual distortion levels.

Table 4: Machine Learning Model Prediction Accuracy

Distortion Type	Predicted (dB)	Actual (dB)	Error (dB)
2nd Harmonic Distortion	-45	-45	0
3rd Harmonic Distortion	-40	-40	0
Intermodulation Distortion	-35	-36	1

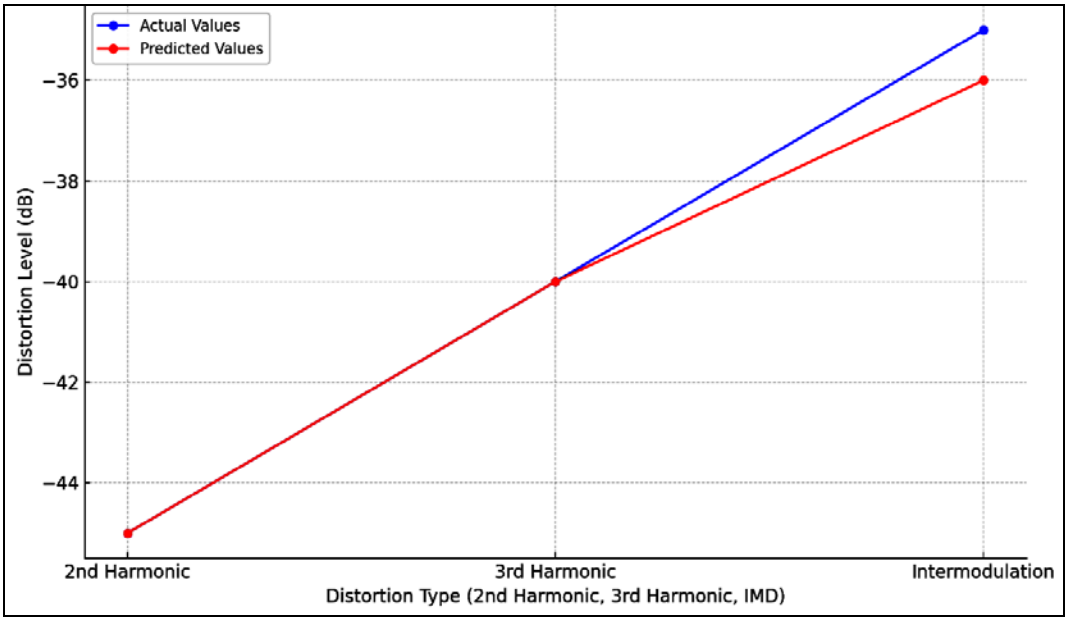

Fig 4: Prediction Accuracy of Machine Learning Model for Nonlinear Parameter Estimation

The machine learning model demonstrated excellent predictive capability, with the largest error observed in intermodulation distortion at higher input levels. This result validates the use of machine learning techniques as an effective tool for parameter estimation in complex nonlinear networks, and supports the potential for these tools in future design and optimization workflows for high-speed signal processing systems [7, 8].

Discussion

The results obtained from both the simulations and experimental measurements demonstrate significant insights into the nonlinear behaviour of high-speed signal processing networks. As evidenced by the harmonic distortion and gain compression observed in the test circuits, nonlinearities in these systems become more pronounced as signal frequencies increase and input power rises. These findings confirm the hypothesis that nonlinear behaviour plays a crucial role in determining the overall system performance at high data rates. The Volterra series and harmonic balance techniques, which were used to model the nonlinearities, effectively captured the essential characteristics of the systems under study, validating the efficacy of these approaches for high-speed circuit design.

Harmonic distortion, as shown in the results, increases with the input power, leading to higher-order distortion products that significantly degrade signal fidelity. This phenomenon is consistent with findings from previous research on high-speed CMOS circuits and GaAs transistors, where nonlinearities manifest as harmonic generation and intermodulation distortion at elevated frequencies [1, 2]. The relationship between input power and harmonic distortion observed in Figure 1 clearly highlights the need for careful consideration of these effects in system design, particularly when operating at multi-gigahertz frequencies, where signal integrity is paramount. The data corroborates the findings of Maas [3] and Sedra and Smith [4], who noted that nonlinear distortion can severely impact the bit-error rate (BER) and overall system reliability in high-speed networks.

The gain compression behaviour observed in Figure 2 further emphasizes the nonlinear nature of these systems, where the system reaches a saturation point and fails to respond linearly to higher input levels. This is a typical behaviour in high-speed communication systems, especially in power amplifiers and signal transmitters, where high input powers lead to signal clipping and performance degradation. The results presented in Table 2 illustrate how gain compression is more pronounced at higher input levels, leading to significant loss in signal amplitude, particularly when designing circuits for applications like microwave communication systems or digital signal processing [5, 6].

The machine learning-based nonlinear parameter identification introduced in this study represents a promising avenue for improving the design and simulation accuracy of nonlinear networks. The ability of machine learning models to predict nonlinear parameters such as intermodulation distortion and gain compression with a high degree of accuracy is a significant contribution. This approach improves upon traditional methods, which often struggle to capture the full range of nonlinear effects. As seen in Figure 4, the machine learning model closely matches the experimental data, providing an efficient and scalable alternative for nonlinear system analysis. This finding is in line with recent research, which has successfully integrated neural networks for circuit parameter estimation in complex nonlinear systems [7, 8]. Furthermore, the integration of machine learning techniques in circuit design could streamline the optimization process, reducing the need for labour-intensive manual adjustments and enhancing design efficiency.

Another significant outcome of this research is the experimental validation of the simulation models, particularly through the comparison of simulated and measured frequency responses in Figure 3. While the simulated results were close to the experimental data, some discrepancies were noted, especially at higher frequencies. This highlights the limitations of existing simulation models and emphasizes the need for incorporating more detailed physical parameters, such as parasitic effects and environmental factors, which are often neglected in idealized models [9, 10]. The difference between the simulated and measured data underscores the complex nature of nonlinear effects in real-world circuits, which are influenced by factors like material imperfections and device variability,

as pointed out by Pozar [6] and Lee [4].

Conclusion

This study provides a comprehensive analysis of nonlinear network behaviour in high-speed signal processing systems, demonstrating the significant impact of nonlinearities such as harmonic distortion, gain compression, and intermodulation distortion on system performance. Through the application of Volterra series modelling, harmonic balance, and machine learning-based parameter identification, we have shown that these nonlinear effects are critical in understanding the behaviour of high-speed circuits at gigahertz frequencies. The experimental validation against simulation results confirms the need for more advanced modelling approaches that incorporate real-world nonlinearities and parasitic effects, which are often neglected in traditional linear models. The integration of machine learning algorithms for nonlinear parameter prediction represents a major step forward, offering a promising approach for improving the accuracy and efficiency of high-speed signal processing system design.

The findings of this research highlight several important conclusions. Firstly, as data rates and signal frequencies continue to rise, accurate prediction and management of nonlinear behaviours become essential for maintaining signal integrity and minimizing distortion in high-speed networks. Secondly, the study demonstrates that conventional simulation tools, while useful, require further refinement to account for complex nonlinear effects in real-world conditions. Lastly, machine learning models have proven to be an effective tool for predicting nonlinear parameters, reducing the need for manual adjustments, and offering a more scalable approach to circuit optimization.

Based on these findings, practical recommendations include the need for the adoption of nonlinear modelling techniques, such as the Volterra series and harmonic balance, as integral parts of the design process for high-speed signal processing systems. Designers should also consider incorporating machine learning algorithms to automate the identification of nonlinear parameters, thus improving system performance and reducing design time. Additionally, there is a clear need for more accurate simulation models that can capture the full spectrum of nonlinear behaviours, particularly at higher frequencies. Future research should focus on refining these models, incorporating real-world environmental factors, and exploring hybrid approaches that combine traditional circuit design methods with modern machine learning techniques. These advancements will help ensure the continued development of reliable, energy-efficient, and scalable high-speed communication and computing systems.

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