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A Review of Digital Predistortion Algorithms for High Power Amplifiers in SWIPT Enabled Networks

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ABSTRACT

Simultaneous Wireless Information and Power Transfer (SWIPT) enabled networks are served by High Power Amplifiers (HPAs) which are pivotal in the modern wireless communication system. As a result, SWIPT-enabled networks suffer from hardware impairment which results in nonlinearity and in-phase and quadrature imbalance problems in HPA. These problems distort the signal constellation during the decoding operation which deteriorates the system detection rate. Mitigating these problems requires the use of Digital Predistortion (DPD) algorithms. This study reviews the advances in DPD algorithms for HPA technology suitable for SWIPT-enabled applications. This review provides the state-of-the-art of DPD algorithms in HPAs and provides future directions for the improvement in the effectiveness of HPAs in SWIPT-enabled networks for self-sustainability and efficient wireless communications.

INTRODUCTION

Wireless communication technologies have grown significantly over the last decade, driven by increased mobile connectivity and the proliferation of sensor devices. Given the growing number of mobile users requiring real-time data transfer, it is critical to integrate self-sustainable energy-efficient power solutions (Ahmed *et al.,* 2024). The revolutionary solution Simultaneous Wireless Information and Power Transfer (SWIPT), which allows for the simultaneous transmission of data and power, solved the energy problem for various applications on emerging networks such as the cooperative networks, Internet of Things (IoTs) and Wireless Sensor Networks (WSNs) (Ojo *et al*., 2019; Karim *et al*., 2024).

According to Nair and Kirthiga (2022), High-Power Amplifiers (HPAs) are essential components used for boosting weak signals in SWIPT-enabled networks. However, the nonlinearities and in-phase-and-quadrature (IQ) imbalances exhibited by HPAs distort the signal constellation during the decoding operation which deteriorates the system detection rate. Recent advances in Digital Predistortion (DPD) algorithms and adaptive amplifier design have enabled effective HPA performance while mitigating the nonlinearity distortion and generally increasing signal integrity. However, meaningful communication is difficult to establish due to the presence of channel defects and varying energy harvesting effectiveness as network circumstances change (Nair *et al.,* 2023).

In terms of communication protocols, the use of HPAs under SWIPT frameworks is attempting to improve communication protocols while also developing rational and eco-friendly approaches that can operate effectively with renewable energy sources. Instead of forecasting signal amplification improvements, this seeks to determine the influence of future systems for next-generation wireless communication in terms of energy transfer efficiency. This study summarizes the contemporary SWIPT difficulties and prospects for the evolution of resilient and sustainable wireless networks, with a focus on HPAs utilized in SWIPT applications (Li *et al.,* 2024; Chen *et al*., 2021).

High Power Amplifiers in SWIPT Systems

In wireless communication systems, particularly within SWIPT-enabled networks, the high-power amplifier plays a crucial role by simultaneously transmitting signals and extracting energy. HPAs amplify weak wireless signals into robust signals capable of traversing distances, thereby facilitating communication between wireless devices (Zhang *et al.,* 2021). The amplified power output results in a reduction of signal degradation and power transfer efficiency. Table 1 presents various classes of amplifiers which have been developed to address the issues in HPA design.

Table 1: Summary of the key characteristics of different HPA classes

Amplifier Class	Efficiency	Linearity	Distortion	Typical Applications
Class A	Low	High	High	High-quality audio
Class B	Moderate	Moderate	Moderate	Broadcast stations
Class AB	High	High	Low	Communications
Class D	Very High	Low	Very Low	Power electronics
Class E	Superior to Class D	Moderate	Moderate	Wireless communications

Recent advancements in HPA design focus on enhancing power efficiency and reducing nonlinear characteristics. Advancements in power amplifier technology through the implementation of adaptive control systems and the utilization of DPD algorithms improve performance while decreasing transmission energy consumption by minimizing signal distortion. Improvements in HPA design introduce several challenges, including heat management, hardware impairments, power consumption, and signal distortion within the mobile network system (Duc *et al.,* 2012). This review examines the existing methods employed to improve the operational flexibility of HPAs across diverse working environments, with a particular emphasis on mobile and remote implementation contexts.

Digital Predistortion Algorithm for Nonlinear Distortions Mitigation

The digital pre-distortion algorithms are potential solutions to mitigate the distortions exhibited by HPAs from their nonlinear amplifiers' characteristics. The DPD algorithms act as a compensator which modifies the input signals so that the amplifier reaches its maximum output linearity potential. SWIPT-enabled networks require DPD algorithms because they support maximum performance through simultaneous power and data transfers to achieve improved efficiency together with minimized distortion.

The implementation of the Memory Polynomial Model (MPM), Volterra Series (VS), Generalized Memory Polynomial (GMP) and Machine Learning (ML) or nature inspired approach DPD methods have been used to eliminate nonlinear amplifier distortions in SWIPT-enabled networks (Fernández *et al.,* 2024; Ding *et al.,* 2004). These methods enable the assessment and correction of nonlinear real-time HPA effects experienced in SWIPT. The implementation of DPD encounters major obstacles in transmission routes that subject waveform and power requirements to regular variations. The development and application of DPD algorithms by researchers depend on machine learning principles for achieving improved performance results. This methodology allows better real-time adaptation to changes that occur in networking environments (Morgan *et al.,* 2006; Abolade *et al.,* 2022).

Table 2: Comparison of different DPD algorithms

DPD Algorithm	Complexity	Strength	Weaknesses
MPM	Low	Simple, effective in many application	Limited accuracy for highly nonlinear system
VS	High	Accurate for complex systems	Computational expensive
GMP	Moderate	Better accuracy than memory polynomial	High computational demand
ML or Nature inspired	Moderate	Better accuracy	Suffering from premature convergence and hyper parameter selection

Review of High-Power Amplifiers in SWIPT-enabled Networks

HPA is an important element in the SWIPT networks used to maximize the signal power and energy efficiency for wireless communication systems. The reliability of data transfer while supplying power is required in this equipment configuration and is dependent on HPAs. To leverage the continuous advancements in wireless communication, signal transmissions over the channel must minimize non-linear distortions, striving for optimal signal reproduction (Mukherjee *et al.,* 2020).

For HPAs, DPD algorithms are good solutions to mitigate distortions to improve the signal quality and maximize the energy harvesting process efficiency. The variability of channel conditions as well as variation in power requirements constitute the first issue of the current technology. Consequently, SWIPT systems design demands that the technique must be continuously refined to realize high efficiency in several operational domains and to accommodate renewable energy and sources (Ojo *et al*., 2019).

The design of future communication networks requires understanding the signal amplification combined with energy efficiency. A key research area for HPAs is optimizing their ability to provide reliable data transmission while minimizing power consumption, leading to improved stability in erratic network conditions. Table 3 summarizes the existing works in HPA technologies for SWIPT networks, outlining their objectives, methodologies, key contributions and drawbacks.

Challenges in HPA Design for SWIPT Networks

To develop HPA for SWIPT systems, it is essential to figure out various critical challenges to increase data transmission and power transmission capabilities. This presents numerous challenges as power efficiency often clashes with signal quality, and amplifiers must adapt to dynamic network conditions (Mukherjee *et al.,* 2020). However, realistic practical deployment requires innovative solutions for SWIPT systems in emerging networks.

Nonlinearity and Distortion Management

The inherent nonlinearities of HPAs introduce distortions in wireless data transmission and reduce power transfer efficiency in SWIPT systems, resulting in degraded performance quality and compromised energy harvesting capabilities (Mukherjee *et al.,* 2020). Therefore, DPD algorithms effectively mitigate HPA-induced non-linear distortion by proactively eliminating unwanted nonlinear effects, resulting in a linear output signal. The performance of DPD algorithms is constrained by their ability to adapt to real-time changes in network characteristics. To achieve efficient HPA in SWIPT systems, future research must comprehensively address the adaptability of DPD algorithms to the dynamic nature of wireless channels, mobile device mobility, and environmental disturbances.

Power Efficiency and Thermal Management

In SWIPT systems, high-power data transceivers force HPAs to focus on power efficiency. Yet, improving these processes simultaneously demands substantial energy, due to unavoidable heat dissipation. Due to the detrimental impact of temperature hazards on HPA performance, reliability, and longevity, effective thermal management is indispensable (Kang *et al.,* 2020). Amplifier topologies, such as Class D and E, are designed with a focus on power conservation while satisfying performance standards. Excessive heat production poses a significant concern since it diminishes system performance.

To address the challenges posed by operational environments, technological research concentrates on the advancement of enhanced heat dissipation materials and active cooling technologies to enable effective temperature regulation in HPAs under these situations (Fernández *et al.,* 2023). Current research efforts are directed towards the development of energy-optimized HPAs for SWIPT systems, aiming to minimize power consumption and thermal dissipation. In addition, recent works in DPD algorithms for HPA designs that incorporate power-efficient techniques tend to minimize the overall power consumption associated with power amplification. The SWIPT system is significantly more sustainable due to the utilization of contemporary power amplifiers and advanced DPD algorithms.

Table 3: Summarizes of some existing HPA technologies in SWIPT networks

Author(s) & Year	Focus Area	Methodology	Key Contributions	Drawbacks
Mukherjee *et al*. (2020)	MIMO-SWIPT systems	Derive the rate-energy region by considering the HPA nonlinearities and its associated memory effects.	Reduced HPA nonlinearities in the rate-energy region.	The complexity was not considered.
Ahmed *et al.* (2024)	Next-generation wireless networks.	Hybrid digital/analog predistorter with reduced sampling rate requirements.	Developed a predistortion system which uses reduced sampling rates in both the forward path and the feedback path.	Power efficiency and heat management were not considered.
Chen *et al.* (2021)	SWIPT, DPD	Derive the tradeoff between the signal to noise distortion ratio and PA efficiency.	Performance Tradeoff Analysis of Hybrid Signaling SWIPT Systems with Nonlinear Power Amplifiers	Only class A and B amplifiers were considered.
Nair and Kirthiga (2022)	SWIPT networks	Bio-inspired DPD algorithms.	Compared the performance of different bio-inspired algorithms to eliminate nonlinearities in SWIPT networks.	Most of the algorithms may suffers from premature convergence, thereby trapped in local optimum.
Liu *et al.* (2024)	wideband power amplifier	GMP model is employed for the lower segment, a MP model is employed for the middle segment, and a higher-order GMP model is employed for the upper segment.	Developed a Low complexity DPD algorithm for wideband power amplifier.	Its application in SWIPT networks was not emphasized.

Channel Condition Adaptability

The wireless propagation of signals in SWIPT-enabled networks experiences detrimental effects due to environmental factors that cause variations in wireless channel conditions between mobility, interference and ambient changes. The built-in characteristics of these networks cause signal propagation to undergo substantial changes because of the changes in wireless channel conditions. The Operational consistency of HPAs depends on their ability to adapt their responses under different converging conditions. SWIPT-enabled networks need dynamic adjustments as a solution to operate efficiently under different transmission conditions and energy harvesting settings (Guo *et al.,* 2015). It is, however, essential to conduct ongoing research into power amplifier systems that automatically adjust operation in real time using network feedback. For optimal network performance in dynamic channel environments, adaptive HPAs with automated gain, power level, and operating class reconfiguration are essential. For SWIPT systems operating in unpredictable channels, Machine Learning (ML) or nature-inspired approaches provide essential predictive monitoring, enhancing HPA capabilities to minimize distortion and ensure high signal integrity for emerging network applications (Masood *et al.,* 2021).

Future Directions in DPD Algorithms in SWIPT Networks

Recent research employs nature-inspired methodologies to improve DPD algorithm adaptability and efficiency. Machine learning (ML) methods enable networks to identify and adapt to fluctuating conditions, resulting in precise real-time predistortion. According to Feng *et al.* (2022) and Nair and Kirthiga (2022) applying ML techniques enables DPD algorithm optimization, resulting in enhanced SWIPT system performance through the mitigation of nonlinearities and reduction of energy consumption and computational overhead. The future of DPD algorithms in SWIPT systems lies in integrating more advanced, adaptive techniques, including:

- Machine Learning-Based DPD: Further study into machine learning methodologies, such as deep learning, is anticipated to improve the DPD algorithm's flexibility to real-time fluctuations.
- Hybrid Algorithms: It is feasible to integrate conventional DPD techniques with machine learning to diminish computational complexity while maintaining adequate distortion compensation for better signal quality.
- Low-Complexity DPD Algorithms: Researchers should focus on the development of computationally efficient DPD approaches that can be seamlessly deployed in real-time without compromising better quality network performance. These developments will be essential for the scalability of SWIPT systems.

CONCLUSION

High Power Amplifiers (HPAs) are essential for powering data transmission and energy harvesting in SWIPT-enabled networks. Historically, advancements in amplifier technology and DPD algorithms have significantly enhanced system performance; nonetheless, issues persist in managing nonlinearity, optimizing power efficiency, and ensuring adaptability under dynamic network conditions. Next-generation SWIPT networks require future research to incorporate machine learning techniques, adaptive and low-complexity DPD algorithms. These will facilitate the complete actualization of SWIPT system capabilities in supporting sustainable and efficient wireless communication paradigms.

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