Switch-Mode RF Power Amplifiers for Hybrid CMOS/GaN All-Digital Transmitters

Mahdi Javid, Student Member, *IEEE*, Jennifer Kitchen, Member, *IEEE*

Abstract— **In this report a Class-E pulse-width modulated RF power amplifier that uses multilevel discrete supply modulation for base station applications is presented. This work quantifies the efficiency roll-off in multilevel PAs and proposes that pulse-width modulated (PWM) class-E PAs offer the best efficiency roll-off and dynamic range, based on the efficiency profile with power back-off (PBO). The presented technique significantly extends the PBO dynamic range of PWM PAs over prior state-of-the-art solutions. A proof of concept watt-level class-E PA is designed using a GaN HEMT and exhibits more than 65% efficiency at 15dB PBO. This design extends the dynamic range of a PWM class-E PA to more than 6dB for a 50 to 30 percent duty cycle variation and offers an efficiency roll-off of less than 4% per dB. The proposed circuit demonstrates an increasing average drain efficiency with power back-off when reducing the PA supply voltage.**

***Index Terms*— RF Power Amplifiers, Class-E, GaN, Pulse-width modulation, Efficiency, Dynamic Range, Supply Modulation**

I. INTRODUCTION

THE high peak-to-average power ratios (PAPR) of modern communication standards (e.g. LTE) require base-station power amplifiers (PAs) to have a large output power dynamic range and maintain a high efficiency profile over their power range. Switch-mode RF power amplifiers (SMPAs) have been demonstrated to achieve highest reported efficiencies when using GaN HEMT devices. SMPAs are also highly desirable for enabling all-digital transmitters. However, due to the non-linear operation of SMPAs, they are traditionally implemented for processing constant-envelope signals for applications such as radar. Various amplitude modulation techniques have been developed to adopt SMPAs for non-constant envelope applications. Such techniques include polar supply modulation, linear amplification using non-linear components (LINC), and pulse-width modulation (PWM). However, these techniques suffer from limited dynamic ranges, low-efficiency in deep power back-off (e.g. 10 dB) or require a wide-band linear supply modulator that significantly degrades the total efficiency. More recent advances in multilevel SMPA architectures combine a fine resolution power modulation method, typically controlled at the input signal, with a coarse resolution power control method, which can be implemented by varying the supply. This work emphasizes the importance of efficiency roll-off versus PBO when choosing PAs for multilevel operation and proposes an architecture that uses a PWM class-E PA in combination with multilevel discrete supply modulation (Fig.1(a)) to achieve the highest average efficiency and dynamic range for the same number of supply levels in comparison with prior multilevel works. The presented architecture exploits the desirable efficiency roll-off exhibited by PWM class-E PAs and addresses the well-known problem of pulse swallowing in PWM PAs. Furthermore, this work presents a class-E PA that is optimized for PWM operation) and demonstrates an enhanced output power sensitivity to duty cycle variation in comparison to prior art. This differs from typical class-E PA design that optimizes for maximum efficiency at a fixed conduction angle and peak power. The proposed architecture uses only one power device and can lend itself to integration with a CMOS driver/digital modulator IC, forming a hybrid CMOS/GaN solution to minimize implementation costs and allow for a holistic digital transmitter. To the best of the authors' knowledge, this is the first time that a class-E PA is optimized for PWM operation, and a discrete supply-modulated PWM class-E for RF base stations is reported. The presented design technique has been demonstrated through a prototype GaN class-E PA, and measurement results are presented in this report.

II. PROPOSED METHOD AND RESULTS

The presented architecture uses a class-E PA that is optimized for PWM input signals and extends the PA's dynamic range and efficiency by using a minimal number of discrete supplies and switching between them, as illustrated in Fig. 1(a). In order to study various attributes of the proposed PA system, a mathematical class-E behavioral model has been developed. The highest efficiency and output power are achieved at 50% duty cycle, and the power back-off is limited to approximately 3dB dynamic range when the duty cycle is limited to a minimum of 30% to avoid input signal pulse swallowing, which is a common phenomenon of PWM systems as shown in Fig. 1(b). The proposed idea of operating PWM class-E PAs with multilevel supply voltages is explored using the ideal class-E model. Comparison between the results in Fig. 1(c) shows that PWM class-E has over 25% efficiency increase at 12dB PBO

Mahdi Javid and Jennifer Kitchen are with School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287 USA e-mail:(mahdi.javid@asu.edu)

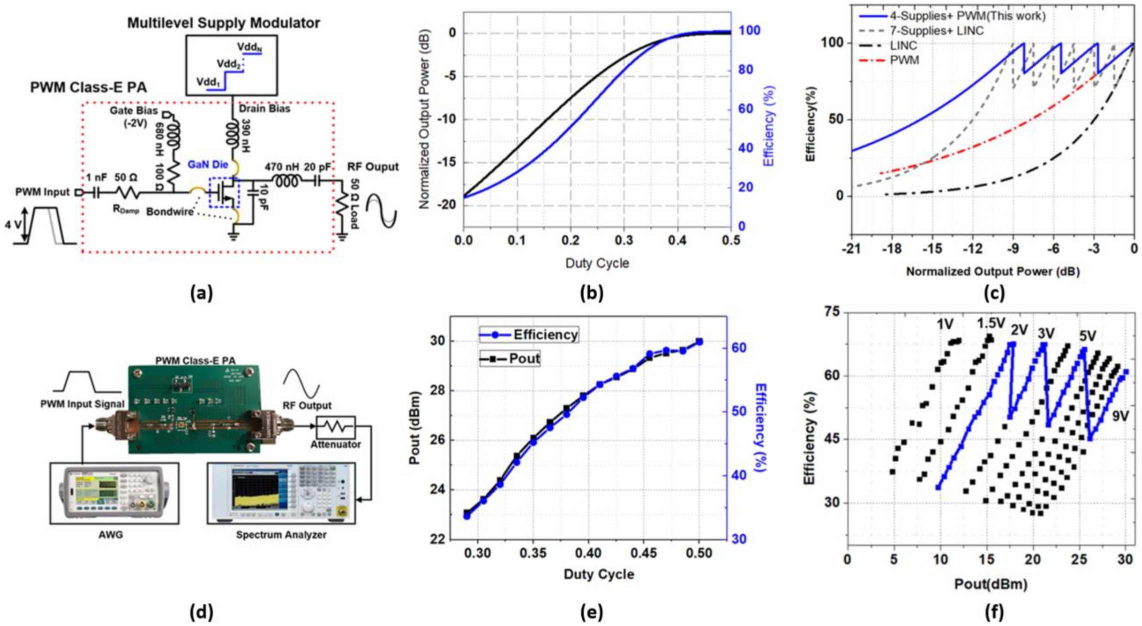

Fig. 1 (a) Proposed System with Implemented PWM Class-E PA (b) Ideal class-E Power and Efficiency versus Duty Cycle (c) Efficiency vs. PBO comparison (d) Implemented Circuit and Measurement Setup (e) Measured Output Power and Drain Efficiency vs. Duty Cycle (f) Measured Efficiency Versus Output Power (Pout) for various supply voltage levels (black). 4-level supply switching at 4dB backoff per supply (blue).

compared with the multilevel LINC. Furthermore, the presented architecture only requires 4 supplies, whereas previously proposed architectures need greater number of supply voltage levels (e.g. 7 for this case) to achieve the same PBO dynamic range. Increased number of supply levels generally correlates to higher circuit complexity and lower total efficiency and linearity for high PAPR signals. Therefore, the proposed architecture overcomes the barrier associated with pulse-swallowing and enables substantially higher dynamic range and efficiency compared with prior works. A proof of concept 1W class-E RF power amplifier is designed with its schematic shown in Fig. 1(a) and (d). The PA achieves more than 6dB dynamic range for 30%-50% duty cycle variation, thus demonstrating successful class-E design optimization for PWM operation as shown in Fig. 1(e). Fig. 1(f) shows measured efficiency versus output power for various supply voltages, where the change in output power is achieved through both duty cycle and supply voltage variation. These results display less than 15% efficiency roll-off per 3dB back-off, and the results validate the proposed concept of using PWM in combination with multilevel supply voltages to increase average efficiency for high PAPR signals. A potential PWM and supply voltage trajectory has been highlighted (blue line) in Fig. 1(f) to achieve more than 20dB PBO with only four supplies, and over 65% drain efficiency at 12.5dB PBO. The concept of multilevel PWM class-E for base-station PAs is introduced and validated through simulation and measurement. This work demonstrates that the PWM class-E's superior efficiency roll-off with power back-off can be exploited to enhance the average efficiency and total dynamic range of multilevel SMPAs. The presented concept allows a PWM class-E PA to achieve higher dynamic range and efficiency by using a minimal number of discrete supplies and switching between them. For the first time, this work also presents an optimized class-E PA for PWM operation to achieve more than 6dB dynamic range in comparison with 2.5dB-4.8dB from prior art. The presented PA shows increasing drain efficiency with PBO when fixing the duty cycle and reducing the supply voltage, thus making this topology a desirable candidate for high PAPR signals. In addition to presented lumped-element solution a transmission-line version has been designed. The results of this work have been published in [1] and a journal version covering further details and results is in preparation to be submitted.

III. CAREER PLAN AND FELLOWSHIP IMPACT

Currently I am writing my doctoral dissertation and preparing for graduation. I do both enjoy working in industry, and academia. Currently, I am planning to join industry for my next chapter with the possibility of returning to academia in the future as a faculty member at a top tier university. I am truly honored to be a recipient of MTT-S Graduate Fellowship and I would like to express my sincere gratitude toward MTT-Society for this prestigious award, their recognition and support. This award has elevated my career and research significantly and granted me the wonderful opportunity to attend IMS/RFIC 2019 to further my knowledge, and network with many talented members of our technical community. I find the impact of this award on my life and career timeless; I would like to thank MTT-S again for this incredible opportunity and I excitedly look forward to making continuous contribution to our technical society in my future chapters.

REFERENCES

[1] M. Javid and J. Kitchen, "A Multilevel Pulse-Width Modulated Class-E Power Amplifier," 2019 IEEE Radio and Wireless Symposium (RWS), Orlando, FL, USA, 2019, pp. 1-4, doi: 10.1109/RWS.2019.8714254.