Adaptive Pulse Skipping for Power Optimized On-Chip Phased Array Driving for Ultrasound (US) Neuromodulation

Aqamolaei, Masoumeh; Costa, Tiago L.

DOI
10.1109/IUS62464.2025.11201481

Publication date
2025

Document Version
Final published version

Published in
2025 IEEE International Ultrasonics Symposium, IUS 2025

2025 IEEE International Ultrasonics Symposium (IUS) | 979-8-3315-2332-9/25/$31.00 ©2025 IEEE | DOI: 10.1109/IUS62464.2025.11201481

Adaptive Pulse Skipping for Power Optimized On-Chip Phased Array Driving for Ultrasound (US) Neuromodulation

1st Masoumeh Aqamolaei
Microelectronics Department
Delft University of Technology
Delft, the Netherlands
M.Aqamolaei@tudelft.nl

2nd Tiago L. Costa
Microelectronics Department
Delft University of Technology
Delft, the Netherlands
T.M.L.daCosta@tudelft.nl

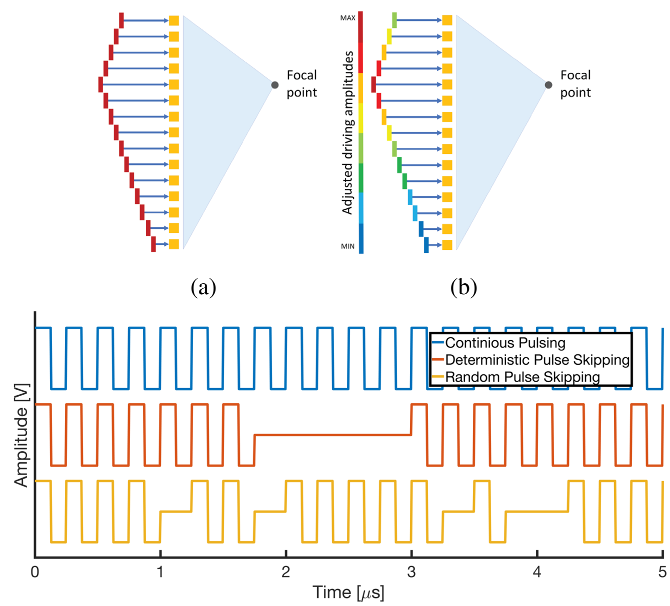
***Abstract*—Power efficiency is critical for enabling the long-term use of implantable and wearable ultrasound (US) neuromodulation systems, where excessive power consumption leads to thermal dissipation and frequent battery replacement. Conventional therapeutic phased arrays typically generate equal pressures from all elements, not taking into account the directivity of each element, and thus the different source contributions to the focal spot, leading to power inefficiency. Although prior methods allow control of source pressure at the element level, such as driver supply control, duty cycle adjustment, or deterministic pulse skipping, they either require complex circuitry, introduce dynamic switching losses, or cause undesirable temporal fluctuations in focal pressure, respectively. To address these limitations, we introduce a novel driving scheme that explores pseud-random pulse skipping to control element-level source pressure and thus optimize power consumption in 2D phased array ultrasound transmitters. The pseudo-random pulse skipping approach allows for regulating the source pressure in each element while preserving a stable pressure at the focal spot, which is required for therapeutic applications. The driving scheme for a single element was implemented in an ASIC, and the result shows that by having different percentages of pulse skipping, we can also modulate the power consumption of the driving channel.**

***Index Terms*—ultrasound neuromodulation, phased arrays, power optimization, beamforming, pulse skipping**

I. Introduction

Decades of technological advances in medical ultrasound imaging have led to new biomedical ultrasound applications such as neuromodulation[1], power delivery[2], and communication[3] in biomedical implants. Microscopic focused ultrasound stimulation[4] μFUS is one of such promising new neuromodulation approaches. In this method, miniaturized ultrasound transmitters deployed under the skull allow higher frequency ultrasound waves to perform neuromodulation, compared to neuromodulation by transcranial focused ultrasound (tFUS)[1]. This leads to high spatial resolution while maintaining high depth of penetration. Although to utilize the full capability of μFUS, the design of a power-efficient system is essential to minimize thermal dissipation and allow the use of battery-powered wearable and implantable form factors. Prior work has been done to improve efficiency using transducer fabrication[5] and circuit design optimizations[6][7]. Conventionally, controlling the power delivered to a load is done by controlling the power supply of the driver circuit[7], the duty cycle of the driving signal[8], or pulse skipping. However, while the first requires extensive and complex switching circuits, the second still imposes dynamic power consumption due to switching; the latter leads

This work was supported by the project UPSIDE (ID 101070931), which has received funding within the framework of Horizon EIC 2021 Pathfinder Challenges by the European Union.



(c)

Fig. 1: The comparison of (a) the conventional approach of driving all the elements in a phased array with the same amplitude regardless of the location of the focal point. (b) The driving amplitude of elements is adjusted based on the location of the focal point. (c) time diagram of different approaches to modulate the power delivered to the elements in a phased array.

to variable pressure over time (Fig. 2b), which may change the resulting bioeffects. Furthermore, conventional therapeutic pulsers typically drive the elements with equal amplitude as in Fig. 1a, not taking into account the directivity of each element, and thus the different source contributions to the focal spot, leading to power inefficiency. In our previous study [9], it was shown that optimizing individual source pressures based on their contribution to the focal point (Fig. 1b) can reduce power consumption by up to 25% to improve power efficiency. This work proposes a pseudo-random pulse-skipping scheme as an alternative to conventional power control methods. In contrast with traditional methods, the proposed scheme allows pulse skipping to be randomly distributed over time for each element Fig. 1c, showing that it can maintain the desired pressure waveform at the focal spot over time (Fig. 2c). Furthermore, we compare this approach with duty cycle (DC) modulation. Even though pressure can be controlled using duty cycle modulation (Fig. 2d), since most of the power consumption is due to switching, the power consumption does not change in this method (Fig. 2e). On the other hand, pulse skipping can modulate both pressure and power consumption (Fig. 2d and Fig. 2e), showing that the proposed approach is beneficial for both pressure and power consumption control. This work is organized as follows: Section II discusses the proposed beamforming channel. Section III explores the electronic circuit design aspect of the work. Section IV presents the measurement results. Section V concludes the paper.

II. Proposed Beamforming Channel Architecture

As shown in Fig. 3, the block diagram of a beamforming channel in a 2D phased array consists of shift registers to store the correct data for the phase information, a digital to time converter(DTC) to generate the desired phase shifts of the beamforming channel in a 2D phased array, a 1.8V to 5V level shifter and a high voltage pulser. In this work, we propose a beamforming channel as shown in Fig. 3. The proposed beamforming channel has an extra sub-block of pseudo-random pulse skipping to modulate the power delivered to the load and the pressure field, allowing control of the power delivered to each element individually. Pulse skipping is traditionally used in DC-DC converters to reduce switching loss at low load conditions, and is implemented using analog comparators, leading to high power consumption [10]. In this work, to minimize area and power consumption, pulse skipping is done utilizing digital circuitry. Random pulse skipping is essential in our application to maintain the uniform pressure field in the focal spot. To this end, a pseudo-random pulse skipping circuit is implemented. Additionally, a full-bridge class D power amplifier has been used to increase the peak-to-peak voltage delivered to the load to twice the high-voltage power supply in comparison to the conventional half-bridge class D amplifiers, where the peak-to-peak voltage delivered to the load is equal to the power supply. The following sections discuss the circuit-level design of each block. This work is designed to drive PZT-5A transducers with a resonance frequency(F_r) of 4MHz.

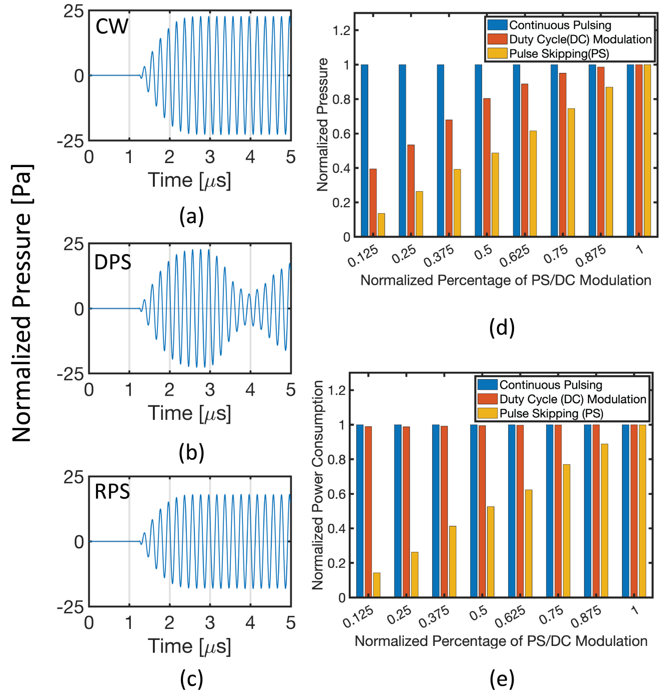


Fig. 2: The comparison of different approaches to modulate the pressure in the focal spot (b) random pulse skipping(RPS) and (c) deterministic pulse skipping (DPS) in terms of pressure at the focal spot in the time domain, also duty cycle modulation and random pulse skipping in terms of (d) normalized pressure in the focal spot and (e) normalized power consumption, for different percentages of pulse skipping/duty cycle modulation.

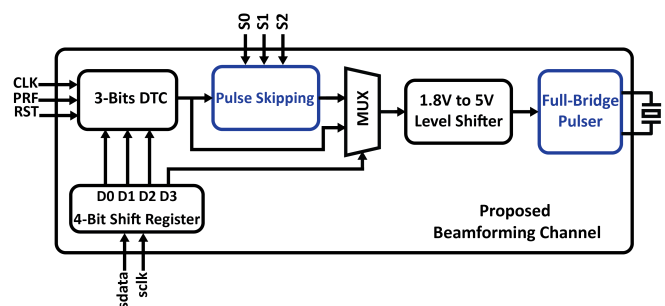


Fig. 3: Block diagram of the proposed beamforming channel with added pulse skipping and using a full-bridge class D power amplifier (pulser).

III. Electronic Circuit Design

A. 3-Bit Digital to Time Converter (DTC)

Beamforming in a 2D phased array transmitter is achieved by introducing precise phase delays to each element so that all ultrasound waves interfere constructively at the desired focal point in a 3D space. This allows the beam to be steered and focused electronically, without mechanical movement. To generate these phase delays, different approaches are mentioned in the literature, such as using a delay locked loop (DLL) [11], a

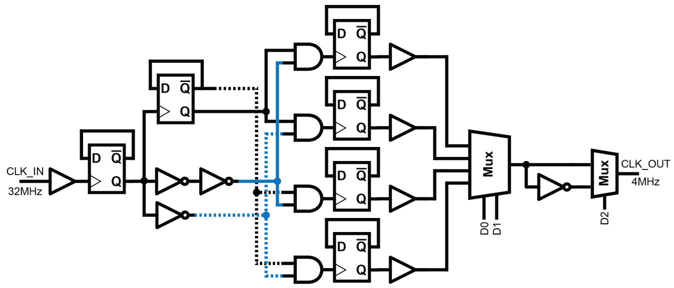
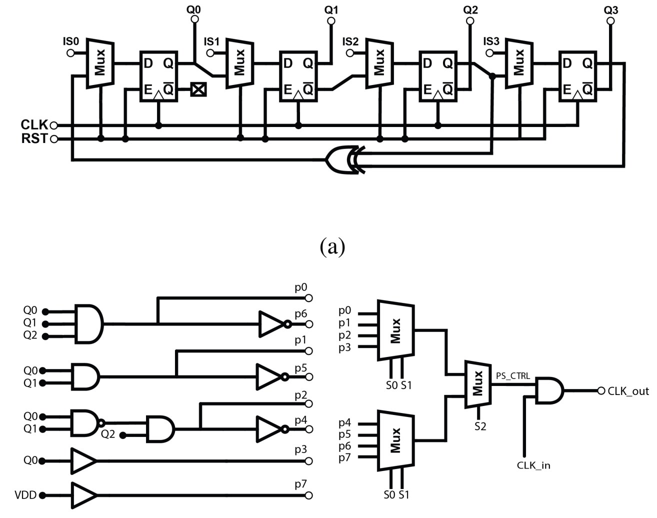


Fig. 4: The circuit diagram of the 3-bit digital to time converter.



(a)

(b)

Fig. 5: 3-bit pulse skipping circuit (a) 4-bit linear feedback shift register to produce a pseudo random bit stream (b) the digital circuitry to generate the 3-bit(eighth levels) of discrete pulse skipping.

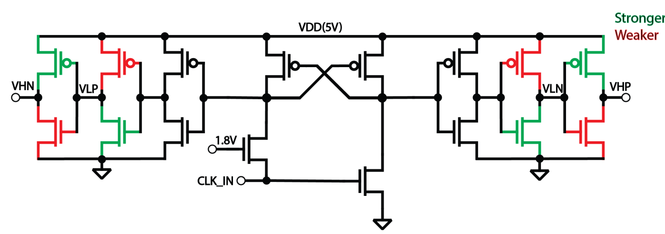


Fig. 6: 1.8V to 5V Level Shifter circuit diagram consisting of a single input level shifter architecture and an asymmetric buffer chain to generate non-overlapping clock signals.

finite-state machine(FSM) and N-bit counters [12], and digital-to-time converters (DTC) [13]. In this work, a 3-bit DTC-based phase delay generation system has been designed, as shown in Fig. 4. This architecture has been chosen based on the fact that for 3-bit phase delays, this architecture consumes much less power and area compared to a DLL and FSM approach. This allows a separate DTC for each channel, simplifying routing and minimizing channel mismatches.

B. 3-Bit Pseudo Random Pulse Skipping (PRPS)

To implement the proposed pulse-skipping scheme, we designed a 3-bit pseudo-random pulse skipping circuitry that enables eight discrete skipping levels corresponding to different probabilities of transmitting or suppressing a pulse. To this end, a 4-bit linear feedback shift register (LFSR) as in Fig. 5a generates a pseudo-random bit sequence to decode the skipping pattern and avoid deterministic artifacts. In addition, the fourth bit is used to increase the randomness of the bit sequence. Then, by feeding the bit sequences from the LFSR to a digital circuit, we implement the eight various levels of pulse skipping shown in Fig. 5b.

C. 1.8V to 5V Level Shifter (LS)

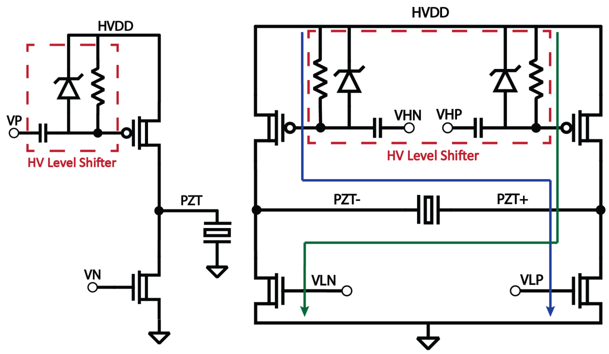
All phase control and pulse skipping circuitry operates on a 1.8V power supply. A driver circuit inside each channel is needed to shift the level of signals from 1.8V to 5V, utilizing 5V transistors. Fig. 6 depicts the level shifter and the buffer chain needed to drive the high-voltage NMOS and PMOS transistors in the high-voltage class D power amplifier. To drive a full-bridge class D power amplifier, realized in this work, four non-overlapping pulses are needed to eliminate the risk of having a low resistance path from the power supply to ground when both the PMOS and NMOS on one side of the full-bridge are on, leading to high power consumption. To generate these non-overlapping clock signals, an asymmetric buffer chain has been used in this work, in a way that by making one path of the signal slower, we ensure that we have a dead-time between the signals.

D. High-Voltage Full-Bridge(H-Bridge) Pulser

In a beamforming channel for ultrasound applications, we commonly need to drive transducers with high-voltage pulses to acquire sufficient pressure using a high-voltage class D power amplifier (pulser). To implement such circuits in this work, TSMC 180nm BCD technology is used. Fig. 7 depicts two types of high-voltage pulser, including the high-voltage level shifter. Fig. 7a shows one of the most common pulsers in the literature, consisting of one NMOS and PMOS as a half-bridge pulser, which can drive the load with a peak-to-peak amplitude of zero to the high-voltage power supply. Fig. 7b shows the high-voltage pulser implemented in this work, known as a full-bridge (H-bridge) pulser. The advantage of having an H-bridge pulser is that you can deliver twice the amplitude in a half-bridge to the load while maintaining the same power supply. The timing diagram of such a circuit is shown in Fig. 7b.

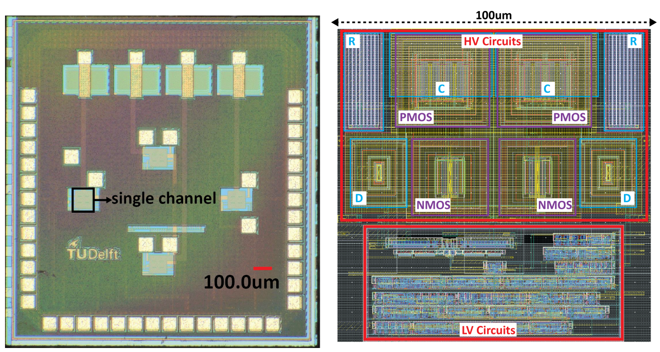
IV. Measurements and Results

The proposed beamforming channel has been taped out in TSMC 0.18-um HV BVD technology. The chip micrograph is shown in Fig. 8a and the layout of the beamforming channel that occupies a silicon area of only $100 \times 100um^2$ is shown



(a) (b)

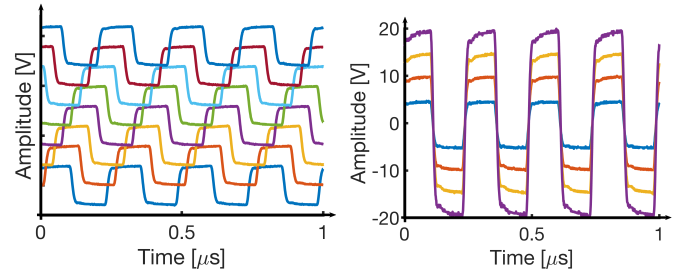
Fig. 7: The high voltage pulser circuit diagram (a) half-bridge class D amplifier (b) full-bridge class D amplifier.



(a) (b)

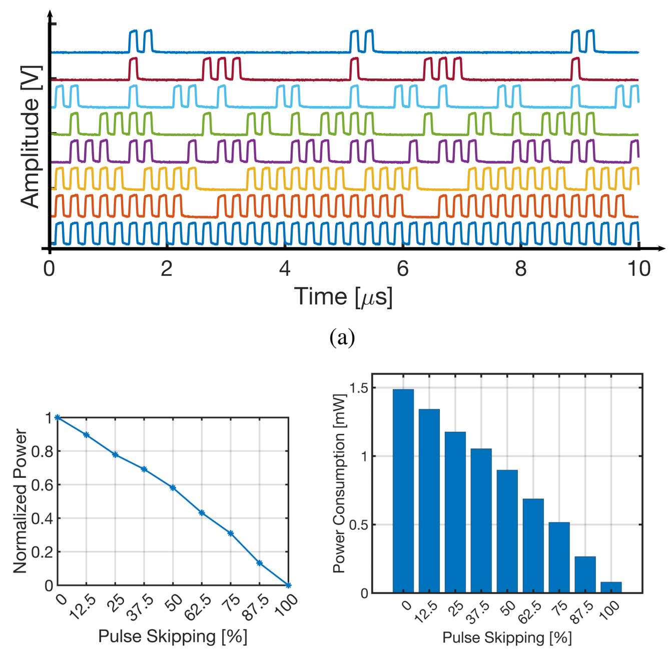
Fig. 8: (a) The chip monograph and (b) layout of a single beamforming channel.

in Fig. 8b. An external 32MHz clock and the data for the phase delays and pulse skipping are provided using an FPGA to analyze the performance of the proposed beamformer. Also, the measurements were done without a load. Fig. 9a shows the output signal of the beamforming channel for eight different configurations of the phased delays, and Fig. 9b shows the output for various levels of the high-voltage power supply. However, since the maximum limit for the available high-voltage probe is 20V, the maximum voltage is limited, even though the beamforming channel can drive the load up to 36V. In the next step, the functionality of the pseudo-random pulse skipping is evaluated by configuring the beamforming channel for eight different levels of pulse skipping. The output waveform for the eight different levels in Fig. 10a shows that the channel can generate these eight levels of pulse skipping. Furthermore, Fig. 10b demonstrates that by modulating the percentage of pulse skipping, the power consumption of the beamforming channel is also modulated with a linear transfer function. Fig. 10c shows the power consumption of the beamforming channel for the eight different levels of pulse skipping, indicating that by increasing the percentage of pulse skipping, the power consumption of the beamforming channel decreases.



(a) (b)

Fig. 9: Measured output waveforms of the beamforming channel for (a) various phase delays and (b) different power supply levels.



(b) (c)

Fig. 10: Measured (a) output waveforms of the beamforming channel, (b) normalized power consumption transfer function, and (c) power consumption of a single beamforming channel, for eight different percentages of pseudo-random pulse skipping.

V. Conclusion

This paper presented a power-optimized beamforming channel architecture for 2D phased-array ultrasound neuromodulation. By introducing a random pulse-skipping scheme, Simulations demonstrated that source pressure at each element can be controlled while preserving a stable focal spot pressure, thereby overcoming the limitations of deterministic pulse skipping and duty-cycle modulation. A compact 3-bit digital-to-time converter, a 1.8V to 5V level shifter, and an 8-level pseudo-random pulse skipping circuit were implemented in 0.18-μm HV BCD technology, enabling adaptive pressure and power modulation with minimal area and power overhead.

Measurement results confirmed that the proposed scheme provides control of the power consumption in eight discrete levels with a nearly linear transfer characteristic. Furthermore, the integration of a full-bridge Class-D power amplifier doubled the peak-to-peak output voltage compared to conventional half-bridge drivers without requiring a higher supply voltage, enhancing pressure generation efficiency. Overall, the proposed architecture achieves both flexible beamforming and adaptive power optimization, paving the way for scalable, energy-efficient phased-array transmitters for implantable and wearable ultrasound neuromodulation systems.

References

[1] Y. Tufail, A. Matyushov, N. Baldwin, *et al.*, "Transcranial Pulsed Ultrasound Stimulates Intact Brain Circuits," *Neuron*, vol. 66, no. 5, pp. 681–694, Jun. 2010.

[2] C. Shi, V. Andino-Pavlovsky, S. A. Lee, *et al.*, "Application of a sub-0.1-mm 3 implantable mote for in vivo real-time wireless temperature sensing," *Science Advances*, vol. 7, no. 7, pp. 1–9, May 2021.

[3] Y. Zhang, P. Muthuraman, V. Andino-Pavlovsky, I. Uguz, J. Elloian, and K. L. Shepard, "Augmented ultrasonography with implanted CMOS electronic motes," *Nature Communications*, vol. 13, no. 1, Dec. 2022.

[4] H. S. Gougheri, A. Dangi, S.-R. Kothapalli, and M. Kiani, "A Comprehensive Study of Ultrasound Transducer Characteristics in Microscopic Ultrasound Neuromodulation," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 13, no. 5, pp. 835–847, 2019.

[5] G. K. Wardhana, N. J. Burghoorn, M. Mastrangeli, and T. L. Costa, "Silicon-integrated Piezoelectric Focused Ultrasound Transducers with PDMS-based Phasing Fresnel Lens for in vitro Ultrasound Neuromodulation," *Authorea Preprints*, Feb. 2025.

[6] P. Guo, Z. Y. Chang, M. A. Pertijs, and T. L. Costa, "A Single-Inductor-Based High-Voltage Transmit Beamformer for Wearable Ultrasound Devices Achieving 88% fCV2Power Reduction," in *IEEE International Solid-State Circuits Conference*, Institute of Electrical and Electronics Engineers Inc., 2025.

[7] I. Bellouki, N. N. Rozsa, Z. Y. Chang, Z. Chen, M. Tan, and M. A. Pertijs, "An Amplitude-Programmable Energy-Recycling High-Voltage Resonant Pulser for Battery- Powered Ultrasound Devices," *IEEE Journal of Solid-State Circuits*, vol. 60, no. 6, pp. 2048–2059, 2025.

[8] J. Blackmore, S. Shrivastava, J. Sallet, C. R. Butler, and R. O. Cleveland, "Ultrasound Neuromodulation: A Review of Results, Mechanisms and Safety," *Ultrasound in Medicine and Biology*, vol. 45, no. 7, pp. 1509–1536, Jul. 2019.

[9] M. Aqamolaei and T. L. Costa, "2D Phased Array Driving Scheme Optimization for Ultrasound Neuromodulation," in *2024 IEEE Ultrasonics, Ferroelectrics, and Frequency Control Joint Symposium (UFFC-JS)*, 2024, pp. 1–4.

[10] S. Nguyen, K. Yuk, and R. Amirtharajah, "Pulse skipping modulation method for multiple input buck boost converter," in *2018 IEEE 19th Wireless and Microwave Technology Conference (WAMICON)*, 2018, pp. 1–4.

[11] T. Costa, C. Shi, K. Tien, J. Elloian, F. A. Cardoso, and K. L. Shepard, "An Integrated 2D Ultrasound Phased Array Transmitter in CMOS with Pixel Pitch-Matched Beamforming," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 15, no. 4, pp. 731–742, Aug. 2021.

[12] C. Seok, X. Wu, F. Y. Yamaner, and Ö. Oralkan, "A front-end integrated circuit for a 2D capacitive micromachined ultrasound transducer (CMUT) array as a noninvasive neural stimulator," in *2017 IEEE International Ultrasonics Symposium (IUS)*, 2017, pp. 1–4.

[13] H. Rivandi and T. L. Costa, "A 2D Ultrasound Phased-Array Transmitter ASIC for High-Frequency US Stimulation and Powering," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 17, no. 4, pp. 701–712, Aug. 2023.