UltraLight: An Ultrafast Imaging Platform based on a Digital 64-Channel Ultrasound Probe

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***Abstract*—Digital ultrasound probes include the entire analog frontend in their enclosing and are equipped with a standard digital link. This enables to build very cost-effective ultrasound systems as they can be simply connected to a commodity device, such as a desktop PC, tablet or smartphone, running an ultrasound imaging application. Up to now, digital probes have been mainly demonstrated for low-end ultrasound applications and are currently limited to a small number of frontend channels (typically 16). In addition, the available bandwidth at the digital interface (less than 10 Gb/s) limits these devices only to basic imaging modalities.**

In this work, we present an imaging platform built with a digital 64-channel ultrasound probe that supports ultrafast imaging. Our digital probe, called LightProbe, utilizes a 64-element phased array without multiplexing and incorporates a 64-channel 100 Vpp TX/RX stage providing a sample rate up to 32.5 MS/s @ 12 bit. The probe features an optical link interface achieving 25 Gb/s on a standard fiber cable. A Xilinx Artix 7 FPGA is integrated in the probe to manage the optical interface and to provide a high-degree of configurabilty. To the best of our knowledge, this is the first digital probe capable of compounded plane wave imaging. We capture plane waves with peak and average rate of 4.9 kHz and 2 kHz respectively, with a peak link load of 15.36 Gb/s, while consuming just 9.25 W.

***Index Terms*—Ultrafast ultrasound imaging, digital ultrasound probe, ultrasound frontend, system implementation**

I. INTRODUCTION

Medical ultrasound imaging is a widely used diagnostic tool for non-invasive investigation of the human body. Compared to other methods, like X-ray tomography or magnetic resonance imaging, ultrasound imaging equipment is portable, has lower cost, operates without harmful ionizing radiation and provides images in real-time. Even though it is more affordable than most alternative imaging tools, the cost of ultrasound equipment still prevents wide-spread distribution.

A typical medical ultrasound-imaging system consists of two main components: A passive transducer probe that emits and captures the ultrasonic waves and is swiped over the patient body, and a backend system, that contains the analog frontend electronics and the digital processing unit. While in the past custom hardware was required in the backend system to form the ultrasound image from the raw probe signals, nowadays the digital processing is increasingly performed purely in software on powerful GPUs [1], [2], multicore CPUs [3] or DSPs [4]. These new system architectures have not only enabled new imaging modalities (Ultrafast Imaging [5], Vector Flow Estimation [6]), but also reduced system cost, as ultrasound specific hardware is only used for the acquisition of the raw signals. The next step in this evolution are *digital* ultrasound probes, which include the analog frontend and provide a standard digital interface [7], [8]. This allows to further reduce cost by connecting the probe directly to a standard device, such as a desktop or laptop PC, tablet or even a smartphone running an ultrasound software application to perform the processing and to display the rendered image.

However, digital ultrasound probes face two main challenges: First, the required bandwidth to transport the raw data from the probe to the processing system exceeds the capabilities for commodity data links. For example, a 16-channel system sampling 12 b signals with rate of 30 MHz produces 5.8 Gb/s of data, which is already more than what a USB 3.0 link is able to provide. The second challenge is the allowed thermal dissipation within the probe, since the surface temperature of a device in contact with the patient must remain below 43° C in order to comply with the medical safety regulations (IEC 60601-1). Thus, digital probes so far have been mainly demonstrated for low-end ultrasound applications, which operate on very few channels (typically 16) and use time multiplexing to support larger transducer arrays. Therefore, only basic imaging modes are supported. In [9] an imaging system is presented, where a digital probe is connected to a smartphone over a USB 3.0 interface. The probe features an integrated 16-channel frontend, performs on-head beamforming and supports a 128-element transducer array by multiplexing. The MobiUS PE System (MobiSante, USA) and the Philips Lumify (Philips Healthcare, NL) are two commercially available digital heads equipped with USB 2.0 (max. 0.48 Gb/s), which is substantially below the bandwidth required for ultrafast imaging.

State-of-art real-time ultrafast imaging systems such as the Aixplorer (Supersonic Imaging) or DiPhAS [2] still rely on a traditional analog probe that is then connected to a backend system, where analog to digital conversion takes place. These systems adopt the ultrafast system architecture paradigm [5], [7], which proposes that the raw converted signals should be directly fed to a general purpose compute unit such as a GPU. To take advantage of the ultrafast system architecture that allows to employ commodity hardware for advanced processing and enables new imaging modalities, digital ultrasound probes

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must be able to transmit unprocessed digital raw data at rates exceeding 10 Gb/s over a distance of more than one meter.

In this work, we present UltraLight, to the best of our knowledge, the first ultrafast imaging system based only on a 64-channel digital probe and off-the-shelf system components. We build on our earlier concept presented in [10], reduce the power consumption by 23% and demonstrate a fully assembled hand-held ultrasound digital probe, consuming just 9.25 W.

Our transducer probe, called LightProbe, uses a 64-element 4 MHz linear phased-array and is able to generate programmable 100 Vpp bi-polar pulses and provides a sample rate of up to 32.5 MS/s @ 12 b. We address the bandwidth limitation by employing a scalable high-speed optical digital link supporting variable transmission rates (0.5-26.4 Gb/s). The probe integrates a Xilinx Artix 7 FPGA that provides a high degree of in-probe configurability to support different transmit and pre-processing schemes.

Our complete ultrasound imaging system, which we call UltraLight, consists of the LightProbe connected to a standard PC equipped with a NVIDIA GTX1080 GPU, allowing us to render compounded plane-wave ultrasound B-mode images on the GPU from the raw digital samples captured by the probe. In the current configuration, the LightProbe captures and transfers emissions to the PC with a pulse repetition rate of 4.9 kHz, resulting in a 15.36 Gb/s link load.

Compared to other systems using digital probes, we provide 4× more channels and a 5× higher link rate while fully supporting the ultrafast system architecture to enable real-time access to the raw digital sample stream for advanced processing in software. In summary our contributions are:

1) We present UltraLight, a complete ultrafast imaging system based only on our digital probe and off-the-shelf system components.
2) We show a fully assembled hand-held LightProbe 64-channel ultrasound digital probe consuming 9.25 W in peak-performance mode.
3) We introduce novel power management strategies to reduce power consumption by 23% in peak-performance mode (even greater reductions in other operational modes).
4) We implement a configurable 0.5-26.4 Gb/s digital optical link to connect the LightProbe to a standard PC for ultrafast imaging.
5) We demonstrate full system operation in ultrafast plane-wave imaging on the standard PC using a GPU.

In the next section we briefly outline the UltraLight system architecture. Then, we describe our design and implementation in depth. In Section VI, we present imaging results along with power and performance measurements. Finally, we discuss the results and close with conclusions and future work.

II. THE ULTRALIGHT SYSTEM ARCHITECTURE

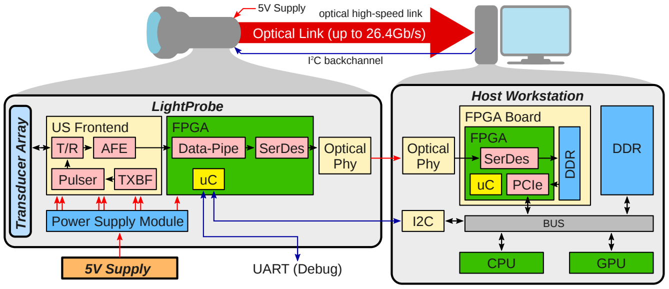

Fig. 1. UltraLight System Block Diagram: Our digital transducer probe, called LightProbe, is connected to a host PC over an unidirectional high-speed optical link. To control the probe an I2C backchannel is provided. The LightProbe is powered by single external 5 V supply. Overall only 4 wires (2x I2C, 5 V, GND) and an optical fiber are required to connect the probe.

Figure 1 shows the system level architecture of our UltraLight imaging system: It consists of our digital transducer probe, LightProbe, connected to a host PC. The LightProbe incorporates a 64-element piezo-electric transducer array, a 64-channel ultrasound receive and transmit frontend, an FPGA for data serialization control and optional processing, a power supply module and several communication interfaces. The probe connects to the host PC over a unidirectional 25 Gb/s optical link. To control the operation of the LightProbe, a low-rate I2C communication backchannel is implemented over an USB link. For debugging, the LightProbe supports an UART console interface. A single external 5V supply powers the LightProbe. The host PC features a powerful CPU as well as a GPU to perform ultrafast plane-wave imaging and is equipped with a connector adapter for the optical link implemented with a FPGA development board.

III. LIGHTPROBE IMPLEMENTATION

In this section, the hardware implementation of the LightProbe (Fig. 1, left) is described in detail. To achieve a compact design in order to meet handheld size constraints, our probe is built out of a highly optimized stack of several printed circuit boards (PCB) as depicted in Figure 2. The motherboard carries a commercial FPGA module and contains the RX stage, power and clock management and the interface plugs. Two boards each providing the TX stage for 32-channels are plugged to the motherboard from both sides. A supply module board generates the required voltages for the frontend.

A. *Piezo-Electric Transducer*

The LightProbe supports transducers with up to 64 elements without multiplexing. Currently the LightProbe is equipped with a custom linear phased-array transducer as depicted in Fig. 2. It features 64 piezo-electric $\lambda/2$ pitched elements. For optimization of energy transfer into the media, the transducer is equipped with a two matching layer system at a center frequency of 4 MHz. The transducer has an elevational height of 10 mm and an acoustic lens focuses the elevational field at a distance of 5 cm (see Fig. 3). Performance losses are minimized by connecting the transducer directly to the motherboard over a flexible printed circuit board.

B. *Ultrasound Frontend*

The ultrasound frontend in the LightProbe provides 64 full-featured transmit and receive channels, in order to emit acoustic pulses and capture and digitize the received echos. Our transmit stage is able to produce per-channel configurable

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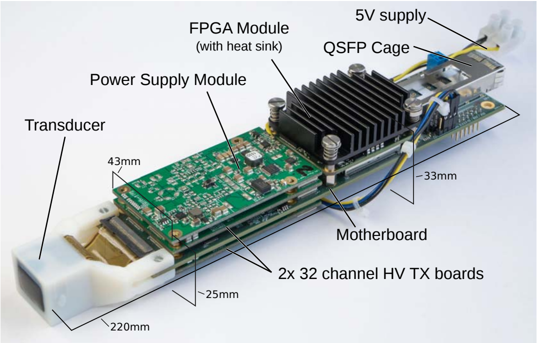


Fig. 2. The LightProbe with its optimized PCB stack and the piezoelectric transducer. The size is 220×43×25 mm^3 without the heatsink.

bipolar ±50 V pulse sequences of up to 64 pulses with a configurable frequency of 0.625 to 15 MHz and a delay range of 102.4 µs with a resolution of 0.78 ns. The receive stage has a bandwidth of 14 MHz (AAF), supports a configurable sampling rate up to 32.5 MS/s at 12 b resolution and integrates a digitally controlled variable gain amplifier (-5 to 31 dB) to compensate for increasing attenuation as the ultrasonic wave travels deeper into the tissue. Compared to our earlier work in [10], we improved the power consumption of the frontend by novel power down modes as well as using a more efficient integrated high-voltage pulser chip (HV7350, Microchip Technology). Moreover, we designed a power supply module integrated into the probe that generates all the required voltages (1.8, 3.3, ±5, ±50) from a single 5 V supply. The LightProbe hardware provides a multitude of options to support different operation modes and power states. In this work, we present the following power states: In ready (RDY), the frontend is fully powered up, i.e. the system is ready to emit pulses and samples all channels. To maximize power savings, the supplies of the frontend can be powered down (PDN). Since it takes around 350 ms to power up the supplies and exit the PDN mode, we additionally provide a STBY mode, which can be entered in 70 µs and left within 600 µs, allowing more aggressive power saving strategies.

C. Optical Link

The optical link is implemented using the Quad Small Form-factor Pluggable (QSFP) standard, which supports four bidirectional 10 Gb/s data-streams over a multi-mode optical fiber. The optical link in LightProbe supports rates between 0.5-26.4 Gb/s and runs the Xilinx Aurora 8b10b protocol. In our demonstrator system, we operate the link at an unidirectional fixed rate of 4×6.25 Gb/s and use a 3 m long 40 G QSFP+ active optical cable (Fiberstore) to connect to the PC.

D. FPGA and Software Architecture

The FPGA integrated in the LightProbe controls the probe and serializes the digital data-streams from the frontend for the optical link. For control, a MicroBlaze microcontroller is instantiated on the FPGA fabric running the LightProbe's firmware, which receives commands from the host PC over the I2C backchannel and configures and controls the ultrasound frontend accordingly. This gives our system a very high degree of freedom and allows easy reconfiguration of the transmit strategy and receive parameters.

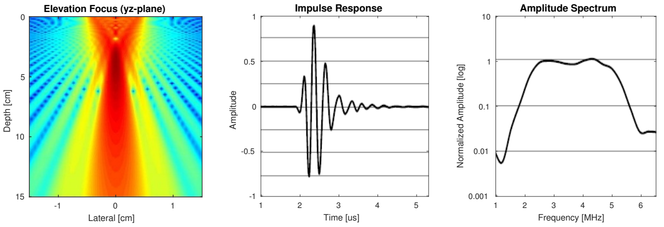


Fig. 3. Impulse response, spectrum and elevation focus of our custom 64 element linear phased array transducer. The elevation focus show the simulated sound pressure of a 5 cm focused continuous 4 MHz sinusoidal wave emission.

IV. Host System Implementation

To demonstrate real-time all-software fast frame-rate imaging, the LightProbe is connected to a host PC providing sufficient processing resources. Besides raw processing power, the PC must provide sufficient interface and bus bandwidth to sink the data streamed from the probe and forward the data to the processing units. For our UltraLight system we use a standard PC with a Quad Core Intel Xeon 3.5 GHz Processor with 64 GB DDR4 memory and equipped with a NVIDIA GTX1080 Graphics Controller with 8 GB RAM.

To interface the optical high-speed link with the PC, we implemented a QSFP to PCIe 3.0 link adapter using a Xilinx Kintex Ultrascale KCU105 development board equipped with a QSFP module. We used this board since it was readily available and only a small fraction of its resources were actually utilized. In practice, the adapter can be implemented much simpler and cheaper, considering that besides providing the QSFP plug, the adapter only provides buffering of the stream until the data is fetched by the host.

V. System Operation

In this section, we outline how an ultrasound imaging application running on the PC interacts with the LightProbe and what operations are performed internally to trigger a transmit-receive sequence until the captured raw data is available on the main memory of PC for processing. After powering up and self-check, LightProbe enters the PDN power saving mode, while it waits for an application to be launched. To start an application, LightProbe is configured over the I2C backchannel for the desired imaging mode by setting the transmit and receive parameters. The optical link is enabled and synchronized and the QSFP-to-PCIe adapter is initialized.

In this state, the system is ready for imaging. When a trigger command is issued over I2C, LightProbe goes into the RDY state and depending on its settings, one or multiple transmit-receive sequences are executed. During each receive phase, LightProbe streams a packet over the optical link containing the raw channel data captured for the preceding transmit event. The QSFP-to-PCIe adapter buffers the packets before the data is transferred to the main memory of the PC for processing. Depending on the probes configuration dictated by the power and frame rate targets of the desired imaging scenario, the

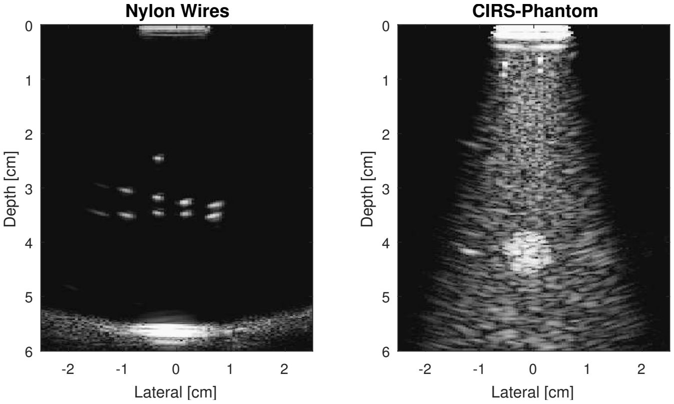


Fig. 4. Images produced with LIGHTPROBE of a nylon wire phantom and a commercial CIRS phantom.

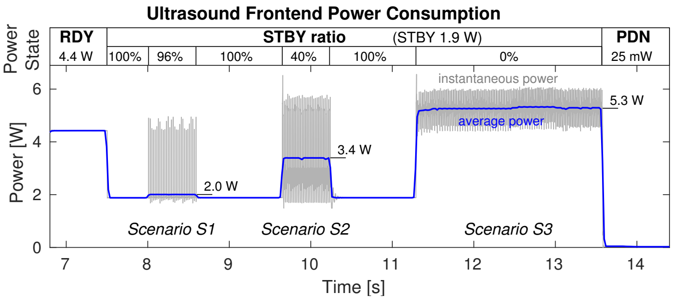
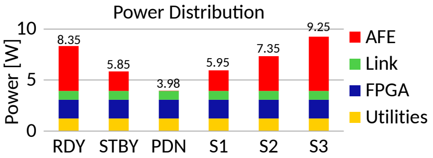


Fig. 5. Power Trace of the Ultrasound Frontend in the LIGHTPROBE over various operation scenarios and power states. The high temporal resolution trace is overlayed with a low-pass filtered version thereof. The average power consumption during the three scenarios including their STBY ratio as well as the three power states (RDY, STBY, PDN) are annotated.



AFE in RDY	4.40 W
Supplies	0.58 W
Receive Path	2.26 W
TR Switches	0.76 W
Transmit Path	0.80 W

Fig. 6. Power distribution for various power states and the different imaging scenarios and ultrasound frontend (AFE) power breakup in RDY power mode.

probe temporally reenters a power saving mode between the sequences. When the sequences are completed, LIGHTPROBE waits in a power saving mode for the next firing command or to be reconfigured for another scenario.

To ease ultrasound application development, we provide a Python library that abstracts away the driver interactions. After having configured the probe, with a simple `data = libLP.getNext()` call, the required commands are issued, the data is transferred to the PC and a data handle is returned.

VI. RESULTS

To demonstrate that the overall system, we configured LIGHTPROBE to perform a plane-wave imaging sequence consisting of 31 plane wave isonifications using different angles from -15° to +15° with 1° increments. Per isonification we configured the system to capture 2048 samples per channel at a rate of 20 MHz to cover a depth of 6 cm. An appropriate time-gain compensation profile was programmed.

On the host system, we forwarded the captured raw digital data to a software beamforming pipeline to render B-mode images: For each of the 31 shots, the processing pipeline computed a subframe by performing interpolation followed by delay and sum beamforming on the GPU using dynamic focusing and dynamic apodization. The 31 subframes were then coherently added and the signal envelope was detected, before the image was converted to the logarithmic domain to be displayed on screen. In Figure 4, we show two B-mode images, one from a nylon wire phantom in a water bath and one from a commercial tissue mimicking phantom (CIRS).

To provide performance figures independent of a specific ultrasound imaging application, we measure the performance of the ULTRALIGHT system on the rate with which we can deliver raw data to the main memory of the host system where it can be forwarded to any available processing pipeline operating concurrently with the acquisition.

To achieve the highest performance, i.e. targeting the maximal framerate with the imaging settings before, we configure the LIGHTPROBE to capture all 31 plane-waves in a burst to minimize synchronization overhead over I2C. In this setup, a burst is captured with a pulse repetition rate of 4.9 kHz resulting in a 15.36 Gb/s peak link load during the receive phases. Considering the 20% coding loss of the link protocol, the link is utilized at 77% (19.2 of 25 Gb/s). Due to the synchronization overheads the average pulse repetition rate over multiple burst is around 2 kHz. The probe consumes 9.25 W in total of which 5.3 W accounts for the frontend.

Figure 5 shows a typical power trace of the ultrasound frontend that demonstrates different power states and how they help reduce the power consumption of the frontend for different imaging scenarios. We consider the following scenarios representing different performance levels: S1 and S2 represent plane-wave B-mode imaging with a fixed framerate of 50 Hz, while S3 is the free-running high-performance mode previously discussed. In S1, one plane-wave is captured to form an image, while in S2 a burst of 31 plane-waves is used to achieve a better image quality. When the probe is not emitting pulses and in the RDY state, the frontend consumes 4.4 W (8.35 W in total). Figure 6 shows a detailed power breakup for this power mode. Given a fixed framerate target, the probe enters the STBY mode consuming only 1.9 W in between data acquisitions. Depending on the scenario, different STBY ratios can be achieved, resulting in power savings. The STBY ratio is annotated in Figure 5 and allows an average frontend power consumption of 2.0 W and 3.4 W for S1 and S2 respectively. During the free-running mode of S3, there is no time to enter the STBY mode resulting in 5.3 W average power consumption. If there are idle periods longer than 350 ms, the frontend can be put in PDN consuming as little as 26 mW.

VII. DISCUSSION

Following a preliminary thermal characterization without the housing, we expect that we will be able to comply with thermal regulations with a smart housing design and thermal

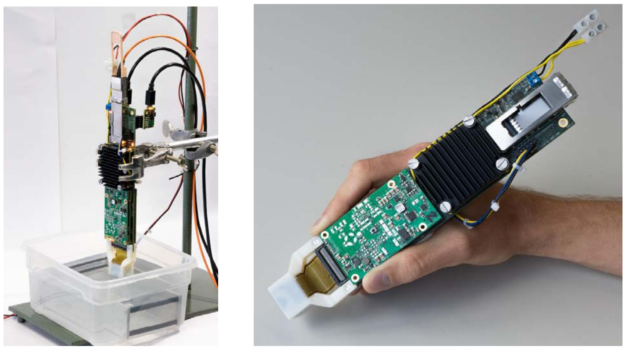


Fig. 7. On the left, the LightProbe prototype in operation connected to the PC with a nylon wire phantom in the water bath. On the left, a person holding the probe comfortably in the hand to illustrate the handheld form-factor.

aware quality of service enabled by our power modes. With the passive heat sink on the FPGA and no special housing or cooling, i.e. as depicted in Fig 7, our digital probe is thermally stable in most operating conditions. Prolonged operation in the most demanding operation scenario (S3) of up to three minutes within prescribed thermal envelope have been reliably demonstrated, where none of the PCB reaches 60° C. Our total power consumption of 9.25 W is comparable to the 16-channels digital probe for mobile imaging reported in [9] that consumes 8.16 W, while complying with thermal regulations.

The burst pulse repetition rate (4.9 kHz) supported by the UltraLight system is given by the imaging settings and how fast the LightProbe can reconfigure its TX frontend between two isonifications. At the time of writing, the triggering mechanism has not yet been optimized for pipelined operation, i.e. the transmit-receive sequence can currently not take place in parallel to data transfer operations, limiting the average pulse repetition rate to around 2 kHz, as reported above. With this optimization, we expect to achieve average pulse repetition rate of 4.9 kHz. As our system interfaces with a standard PC GPU interface, any existing GPU beamformer implementation such as [1], [2] supporting the full data bandwidth of the system can be used for UltraLight as well.

Compared to high-end systems capable of ultrafast imaging such as DiPhAS [2], the Vantage system (Verasonics) or the Aixplorer (Supersonic Imaging), UltraLight offers a promising alternative. Even if it supports only one fourth of the number of channels of these high-end systems, we are able to do so at a much lower cost, power budget and smaller form factor using only off-the-shelf system components apart from the LightProbe, which can be fabricated even in small volumes at the cost of a few k$. Thus, UltraLight fills the gap between mobile and high-end systems, which we believe will further push the application of this technology.

VIII. CONCLUSION

We have presented an ultrasound imaging platform built around a novel a 64-channel digital probe connected to a desktop PC performing real-time plane wave imaging on the GPU. Our UltraLight system demonstrates that digital probes allow to build high-performance imaging system without performance compromises using only a minimal amount of ultrasound specific hardware, which can be confined within the probe handle. As the LightProbe is highly configurable and all processing is done in software, new imaging modalities can be easily implemented by writing the required ”ultrasound app” for our system.

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REFERENCES

[1] B. Y. S. Yiu, I. K. H. Tsang, and A. C. H. Yu, “GPU-based beamformer: Fast realization of plane wave compounding and synthetic aperture imaging,” *IEEE Trans. Ultrason. Ferroelectr., Freq. Control.*, vol. 58, no. 8, pp. 1698–1705, 2011.

[2] C. Risser, H. J. Welsch, H. Fonfara, H. Hewener, and S. Tretbar, “High Channel Count Ultrasound Beamformer System with External Multiplexer Support for Ultrafast 3D / 4D Ultrasound,” in *IEEE Ultrason. Symp. Proc.*, 2016.

[3] A. Kurth, A. Tretter, P. Hager, S. Sanabria, O. Goksel, L. Thiele, and L. Benini, “Mobile ultrasound imaging on heterogeneous multi-core platforms,” in *Proc. 14th ACM/IEEE Symp. Embed. Syst. Real-Time Multimed.*, 2016.

[4] J. Ma, K. Karadayi, M. Ali, and Y. Kim, “Ultrasound phase rotation beamforming on multi-core DSP,” *Ultrasonics*, vol. 54, no. 1, pp. 99–105, 2014.

[5] J. Bercoff, *Ultrafast Ultrasound Imaging*, O. Minin, Ed. InTech, 2011.

[6] C. A. Villagomez Hoyos, M. B. Stuart, K. L. Hansen, M. B. Nielsen, and J. A. Jensen, “Accurate Angle Estimator for High-Frame-Rate 2-D Vector Flow Imaging,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 63, no. 6, pp. 842–853, 2016.

[7] O. M.-G. D. Romero-Laorden, J. Villazón-Terrazas and A. Ibáñez, “Strategies for Hardware Reduction on the Design of Portable Ultrasound Imaging Systems,” *Adv. Break. Ultrasound Imaging*, pp. 243–268, 2013.

[8] T. Di Ianni, M. Hemmsen, P. Llimós Muntal, I. H. H. Jørgensen, and J. Jensen, “System-level Design of an Integrated Receiver Front-end for a Wireless Ultrasound Probe,” *IEEE Trans. Ultrason. Ferroelectr. Freq. Control*, vol. 63, no. 11, pp. 1935–1946, 2016.

[9] S. Ahn, J. Kang, P. Kim, G. Lee, E. Jeong, W. Jung, M. Park, and T.-k. Song, “Smartphone-based Portable Ultrasound Imaging System: Prototype Implementation and Evaluation,” in *IEEE Ultrason. Symp. Proc.*, vol. 1, 2015, pp. 1–4.

[10] P. A. Hager, C. Risser, W. Peter-Karl, and L. Benini, “LightProbe: A 64-Channel Programmable Ultrasound Transducer Head with an Integrated Front-end and a 26.4 Gb/s Optical Link,” in *2017 IEEE Int. Symp. Circuits Syst.*, 2017, pp. 302–305.