

# Designing compact medical ultrasound systems

By John Scampini

OVER THE PAST DECADE, medical ultrasound imaging equipment has experienced a revolution. Advances in integrated electronics have allowed equipment manufacturers to significantly improve the portability and the affordability of this powerful medical tool. What once weighed hundreds of pounds and required a cart for mobility, is now the size of a portable laptop computer. Needless to say, the impact for the medical community and the patient has been profound. In developed countries ultrasound is now utilized at the patient's point of care, which reduces costs and improves outcomes. In developing countries ultrasound imaging is now available to a much larger segment of their large rural populations. The impact of these new, more portable low-cost systems on healthcare worldwide is significant and well received. The future of the technology promises even more advances.

The road to developing these compact imaging solutions has not been easy. There have been, and will continue to be, significant design challenges as manufacturers strive to make these systems more portable, less expensive, and higher in performance. This article will highlight some of the more significant design challenges faced by designers of this equipment.

Designers of compact ultrasound systems must fit the large number of ultrasound transceivers required to produce a high-quality image into the available small space. This is no simple task. Current state-of-the-art systems commonly possess 128 or more of these transceivers.

A typical ultrasound transceiver block diagram is shown in figure 1. To produce an ultrasound image, the transceiver's high-voltage transmitters generate properly timed high-voltage pulses to excite the ultrasound transducer elements and generate a focused acoustic transmission. Acoustic energy from this transmission is reflected by impedance discontinuities in the patient's body, received by the same elements, and routed back to the receive portion of the transceiver.

The receiver consists of a transmit/receive switch (TR switch), low-noise amplifier (LNA), variable gain amplifier (VGA), anti-alias filter (AAF), and analog-to-digital converted (ADC). Each transducer element is connected to an LNA through a TR switch which protects the LNA input from the high-voltage

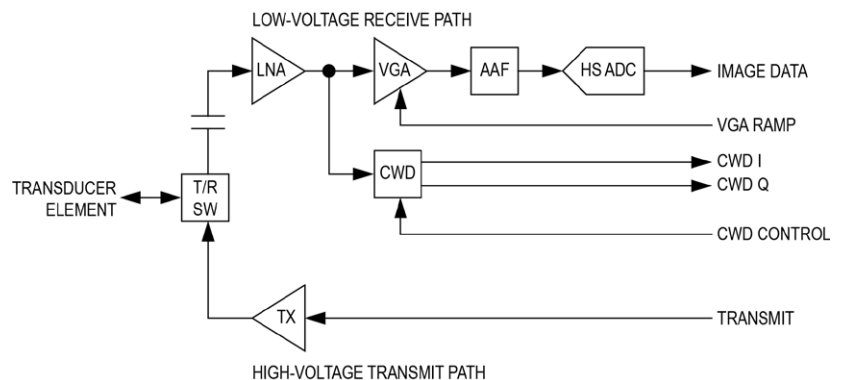


Fig. 1: Ultrasound transceiver block diagram shows the diverse functionality required.

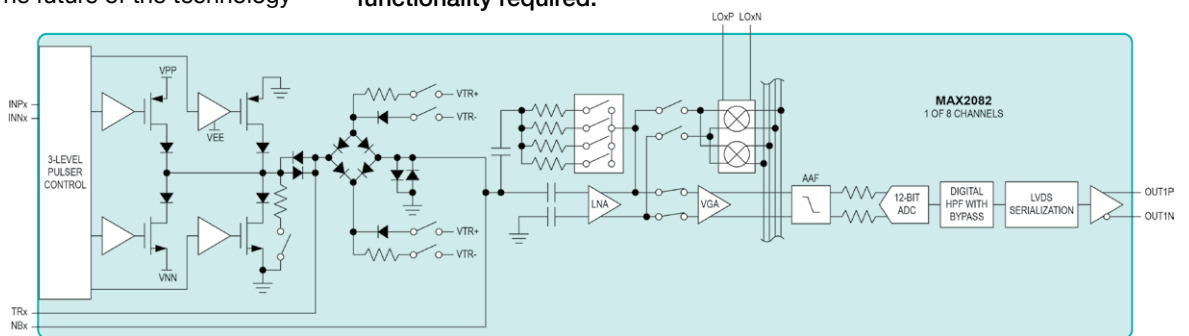


Fig. 2: MAX2082 ultrasound transceiver integrates the full receiver, TR switch, coupling capacitors, and the three level high-voltage pulsers.

transmit signal. The LNA itself provides an initial fixed gain to optimize the receiver's noise performance. The VGA is used to compensate for the attenuation of the ultrasound signals in the body over time which reduces the dynamic range requirements for the subsequent ADC. The AAF in the receive chain keeps any high-frequency noise beyond the normal maximum imaging frequencies from being mapped into the receive band by the ADC. The amplified and digitized signals are delayed and summed in the ultrasound system's digital beamformer to generate a focused receive beamformed signal. The resulting digital signal is used to generate 2D images as well as pulsed-mode Doppler information.

The receiver also has a separate continuous wave Doppler (CWD) receiver/beamformer path after the LNA. In CWD mode, the receiver's dynamic range requirements are very demanding and beyond the range of the VGA/ADC signal path. CWD beamforming can be achieved by mixing the received signals with properly phased LOs and summing the resulting baseband signals. As a result, the CWD receiver block is comprised of high-dynamic-range analog I/Q mixers and programmable LO generators.

As one can see, there is significant functionality in a typical transceiver and getting 128 or more of these into something the size of a PC is a design challenge. Analog IC manufacturers have responded to this challenge with more highly integrated

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solutions. Thus, it is now common to find octal receivers including the LNA, VGA, AAF, and ADC in packages as small as 10x10mm. High-voltage pulsers are also now available in 4- and 8-channel single-package configurations as small as 10x10mm. These advances are significant and have played a key role in enabling the current generation of portable systems. Moving forward, however, there are more integration opportunities.

The MAX2082 octal transceiver – see figure 2 – is an example of the latest advance in highly integrated ultrasound solutions. It includes the full receiver, TR switch, coupling capacitors, and the three level high-voltage pulsers in a single 10x23mm package. This single transceiver saves considerable space, reduces design time, and lowers overall system cost.

The space savings from such a highly integrated transceiver can be dramatic. The integrated TR switch alone represents significant savings. Consider a typical discrete TR switch used in most existing ultrasound systems – see figure 3. There are nine discrete components in this TR switch implementation. In a 128-channel system this represents over 1000 discrete parts for the TR switch function alone!

Figure 4 shows a PCB layout using the MAX2082 for a 128-transceiver channel configuration. The space required is less than 10 square inches, which is less than half the space required for current solutions that use individual octal receiver ICs, octal pulser ICs, and discrete TR switches.

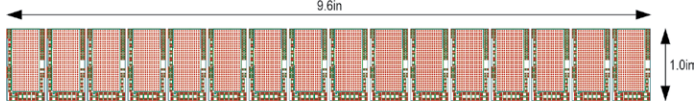


Fig. 4: 128-channel PCB layout using octal transceivers.

### Transceiver power management

Power is also a major concern in these highly integrated designs. Many of these ultrasound systems are portable and must run from a battery for an hour or more between charges. Heat management is also problematic as the component density is very high and the PCBs can be very close together, leaving little room for airflow. The ultrasound transceivers represent a significant portion of the overall system power budget and, therefore, warrant significant design attention.

Over the past 10 years ultrasound receiver power has been cut in half. It is now common to find IC receive solutions including the LNA, VGA, AAF, and ADC that burn less than 150mW per channel. These new-generation receivers also have more flexible power-control features allowing users to trade off power for performance as well as utilize low-power, fast wake-up “nap” modes to conserve power when systems are in non-imaging modes.

There are still more opportunities for future improvement. The TR switch itself, for example, can burn in excess of 80mW per channel, because

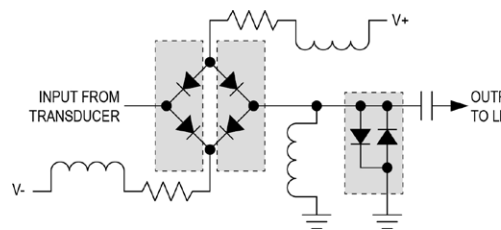


Fig. 3: Transmit receive (TR) switch has nine discrete components. In a 128-channel system, there are over 1000 discrete parts in these switches alone.

significant bias current is required to lower the on-impedance of the diodes to meet necessary noise performance. This is almost as much power as the rest of the receiver! Newer proprietary integrated TR switch designs in products like the MAX2082 transceiver mentioned above achieve better noise performance than these discrete designs for less than 15mW per channel.

### Balancing noise with miniaturization

High levels of integration and low power are obvious design challenges for portable ultrasound systems. Not so obvious are some of the performance issues associated with the miniaturization of this equipment.

### Minimizing in-band noise

Ultrasound systems are extremely sensitive to both radiated and conducted in-band noise and interference in the 2MHz to 15MHz range. The input sensitivity of a single channel can be as low as 1nV/rHz. In typical 128-channel systems, an unwanted signal applied to all inputs can have a processing gain of up to 21dB, depending on channel-to-channel beamforming delay. As a result, an in-band noise signal applied to all inputs as small as 0.09nV/rHz can be visible and appear as an artifact in the image. These artifacts occur so commonly that they are universally called “flash light” artifacts; they resemble a beam of light in the center of a phased array image where the system has the highest processing gain to a common input signal. Signals this small can easily come from a variety of radiated or conducted interference sources in the system.

Ultrasound system designers go to great lengths to physically separate and shield noisy digital circuitry from sensitive analog circuitry, and to control ground loops. Unfortunately, portable ultrasound system designers do not have the luxury of physically separating this circuitry, and shielding can be problematic given the limited space and heat density of most PCBs. As a result, it is extremely common that in-band noise problems occur in these designs, especially when they are so physi-

cally close to noisy single-board PCs commonly used to perform many of the computational and display tasks. Consequently, it is particularly important that proper attention to grounding and shielding be made early in the design process. Trying to modify these highly integrated designs later in the prototype evaluation phase can be extremely difficult and time-consuming.

### Minimizing audio noise

In many cases, low-frequency audio noise can also be a problem and, in fact, is often more difficult to solve. In ultrasound systems blood flow is detected by measuring the small Doppler frequency shift of the reflected transmit signal. Any low-frequency modulation of the transmit signal or the received signal from stationary objects will produce noise sidebands which

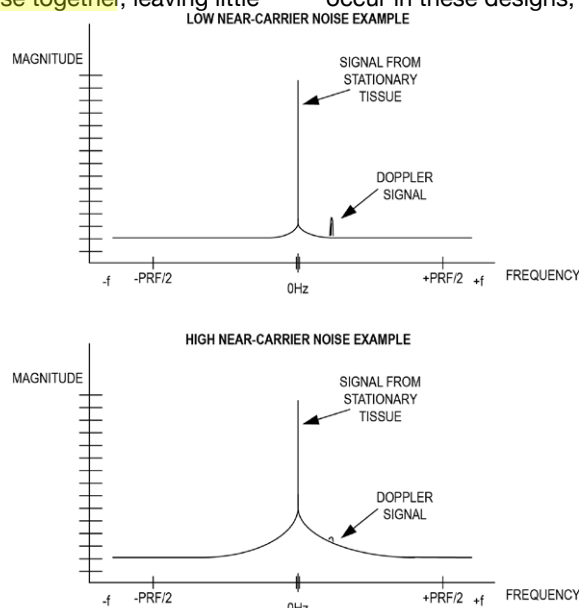


Fig. 5: Doppler near-carrier noise.

can obscure Doppler signals of interest, as shown in figure 5 or produce unwanted “tones” in the Doppler spectrums. In pulsed Doppler applications the ratio of the transmit signal power to the noise at 1kHz offset needs to be less than 140dBc/Hz. For CWD, the requirement is even more demanding at 155dBc/Hz or greater.

There are many sources of this low-frequency noise, but the largest and most common is low-frequency power-supply noise which can cause a host of Doppler problems. It can introduce jitter in sensitive digital transmit and receive clocks which can, in turn, limit the receiver’s dynamic range or produce unwanted Doppler tones. It can also create low-frequency noise on VGA gain control signals that can modulate large received signals from stationary tissue and obliterate weak adjacent Doppler signals.

Power-supply noise in the audio spectrum can only be effectively reduced by active regulation of the supplies. Traditionally, in larger cart-based systems, power-inefficient linear regulators were distributed liberally throughout the system to effectively control this source of noise. In more portable systems this type of solution is quite often not acceptable.

As a result, designers must utilize distributed switching regulators to improve efficiency. Unfortunately, this type of regulation can introduce significant RF in-band conducted and radiated switching noise that is difficult to control, even with proper bypassing. Spectral Doppler is particularly sensitive to this type of noise as the discrete switching frequencies can cause tones in the Doppler spectral displays, a common artifact in these systems.

One way to ensure that this type of noise is not visible is to ensure that the switching-regulator frequency is synchronized to the master clock of the system. In this way, switching noise can be more easily managed out of the Doppler bands of interest, and a high level of efficiency can be achieved.

Considerable attention must be given to the use of switching regulation in these designs to keep power low and avoid difficult-to-solve Doppler artifacts.

### Where do we go from here?

Design engineers agree that designing portable ultrasound systems presents significant challenges. Limited space, managing power within shrinking space constraints, and the demand for higher and higher levels of performance are presenting new and quite significant problems to overcome. Designers need

to judiciously use analog IC solutions that are already highly integrated, are low power, and meet the required levels of performance. They must also anticipate and then perform the necessary detailed system-level design work to avoid the common noise-related problems inherent in these highly compact designs.

The benefits of these new more portable systems are more than worth any design risks. We have already seen the positive impact that these systems have had on healthcare worldwide. There is no reason to believe that this trend will not continue —as long as more highly integrated analog IC solutions become available to the equipment designers of these highly compact medical systems.



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