DIGITAL BEAMFORMING USING NON-UNIFORM OVERSAMPLING DELTA-SIGMA CONVERSION

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ABSTRACT

A promising approach to reduce the complexity of the front-end hardware of an ultrasound imaging system is to utilize oversampling Delta-Sigma ($\Delta\Sigma$) beamforming. Realization of dynamic receive focusing involves signal resampling of uniformly sampled radio frequency (rf) signals using beamforming timing. The resampling (deleting or repeating samples), however, causes a significant increase in the noise floor of the beamformer output. To overcome this problem, we have explored a new digital beamformer employing non-uniform oversampling. To avoid resampling during dynamic focusing, we have used a different sampling clock at each channel to sample rf echo signals non-uniformly at the time instants associated with receive focal points. The performance and validity of the new system are assessed by means of emulations using experimental *3.5* MHz rf data.

I. INTRODUCTION

State-of-the-art ultrasound systems employ a digital front-end electronics, wherein a high-speed multi-bit (8 or 10 bit) analog-to-digital (A/D) converter is invoked on each channel to digitize incoming echo signals [1]. The echo signal at each array channel is typically digitized synchronously at the same uniform clock rate. Effectively, received signals can only be delayed using time increments associated with the sampling period, and the resulting time delay quantization reduces the *SNR* at the beamformer output and causes some grating lobes. Generally, in medical ultrasound imaging, the time delay resolution should be on the order of *32* times the ultrasound frequency [2]. Therefore, with regards to the implementation of digital beamformers, one of the critical difficulties is the high sampling rate requirement of the A/D converters.

There are three different techniques commonly employed in commercial ultrasound systems to relieve the high sampling rate requirement of A/D converters, including interpolate-decimate method [3], baseband beamforming [2] and non-uniform sampling scheme [4].

In interpolate-decimate beamformers, the required delay resolution is achieved by processing the digitized signal at each channel through an interpolation filter [3]. The price for the reduced sampling rate, however, comes here in part hence the interpolation filter (usually a sinc filter) per channel brings stringent digital signal processing requirements.

In baseband beamforming method, the reflected signals are mixed with the carrier and then processed through a low-pass filter yielding the In-phase (I) and Quadrature (Q) components [2]. This method, however, is not practical for low cost applications since variable phase rotator is required on each channel to appropriately focusing the baseband signals.

In non-uniform sampling scheme, focusing delays are employed not to the echo signals but to the sampling clocks [4]. The echo samples, sampled at different instances on each channel, are digitized using a multi-bit A/D converter and then delivered into a first-in first-out (FIFO) buffer. The beam sum is obtained by shifting the delay compensated echo samples to the output side of each FIFO buffer at the same time and performing a summation across the array.

Present systems such as those cited above are still at a point far beyond to meet the requirements for a beamformer-on-chip, which can be used in clinical settings. An elegant way to reduce the beamforming hardware and preclude many difficulties encountered with multi-bit A/D converters, is to exploit oversampled noise shaping principles [5]. Directly replacing the multi-bit A/D converters with single-bit Delta-Sigma ($\Delta\Sigma$) modulators, produces some unexpected noise during dynamic focusing [6]. In this paper, a new dynamically focused oversampled noise shaping beamformer based on non-uniform sampling scheme is presented, which approaches the image quality performance of multi-bit systems.

II. $\Delta\Sigma$ BEAMFORMING USING UNIFORM SAMPLING

In 1993, Noujaim *et. al.* [5] have patented a digital beamforming method which exploits oversampled noise shaping conversion in an effort to reduce the hardware complexity involved in the front-end electronics of an ultrasound imaging system. The general arrangement for such a system is illustrated in Fig. 1.

The echo signals are digitized by single-bit $\Delta\Sigma$ modulators, and the resulting one bit sequence at each channel is stored in a dynamic buffer having variable addressing capability. Dynamic focusing is realized by reading these stored samples under the control of a delay control circuitry, which produces the desired variable addressing for each channel according to the propagation time delays. As shown in Fig. 1, delayed single-bit samples are added together to form the beam sum along with some high frequency quantization noise, which is later suppressed by a single decimation filter at the beamformer end.

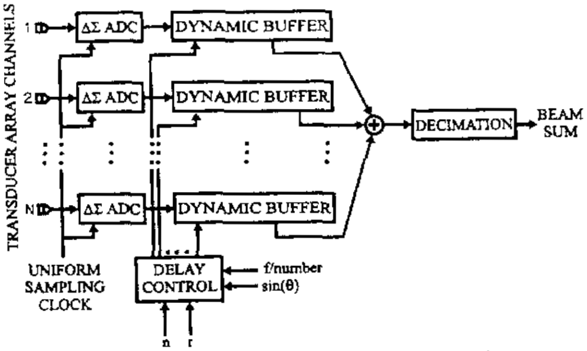

Fig. 1: Block diagram of the conventional ΔΣ beamformer

The oversampled noise shaping beamformer proposed in [5], however, suffers from a fundamental flaw limiting its ultimate use in clinical systems, because the image quality is severely effected by the unexpected noise induced by the signal resampling during dynamic focusing.

The in-band *SNR* performance of an oversampled noise shaping converter is related to the oversampling ratio (*OSR*), which is defined as the sampling frequency divided by two times the input signal bandwidth. In such systems, the samples of the beam sum should be acquired at an oversampled rate, and hence dynamic delays should be changed very rapidly. Consequently, the distance between consecutive focal points should be chosen sufficiently close to achieve an *OSR* that provides the desired in-band *SNR* performance of ΔΣ modulators. On the other hand, dynamic focusing delay patterns for such closely spaced focal points, however, cause signal resampling due to the insufficient time delay quantization and/or acoustical geometry [7].

To clarify the problem, a symbolic representation of beamforming curvatures is demonstrated in Fig. 2, where for simplicity purposes the array is assumed to be focused at its normal direction to ignore steering delays.

In Fig. 2, according to beamforming curvatures, only high portions of clock cycles are highlighted indicating that those samples are needed to form the signal value of focal points. Also note that the repeated samples are filled with a darker color where the beamforming curvatures are coincided at the same resolution cell. Clearly, not all the modulated bits are utilized during dynamic focusing resulting in sample repetitions and/or omissions. More specifically, almost in every channel (except at the array center) some of the consecutive focal points may require the use of the same sample during dynamic focusing. By the way, some of modulated bits are repeated whereas some of those should be disregarded.

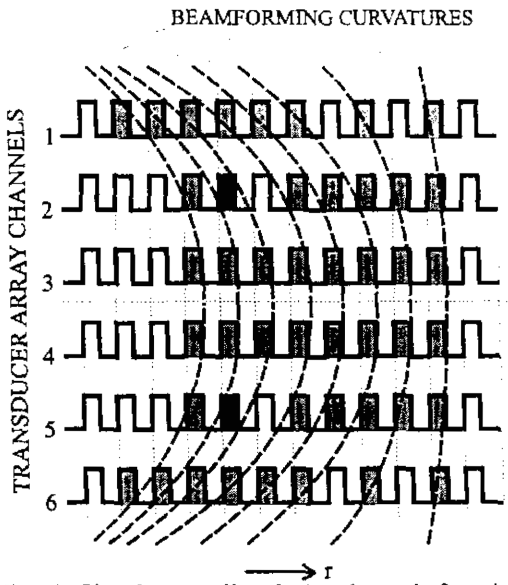

Fig. 2: Signal resampling during dynamic focusing

Under normal operation of ΔΣ modulators, much of the quantization noise lies well outside the signal pass-band. However, repetition and/or omission of some particular bits in the delay structure corrupt the noise shaping property of ΔΣ modulators by folding back some unexpected noise energy at higher frequency into lower frequency where the original signal is much favor to be found [7].

Three different approaches to handle with the sample repetition problem have been recently proposed by Freeman *et. al.* [6], [8] to produce efficient architectures for a high performance ΔΣ based beamformer. The first two approaches are based on the recoding of the modulated bits. Both of the recoding methods are effective in correcting the situation resulted due the signal resampling, however they may negate the simplicity advantage of the beamformer gained by single-bit ΔΣ modulators, because extra bits are required to recode the modulated bits [6].

Freeman *et. al.* [6], [8] have further suggested an alternate solution which maintains the advantage of single-bit ΔΣ modulators by allowing dynamic focusing operation to be performed on one bit data. In this simple approach, ΔΣ converters are forced to take into account the repeated samples in their operation by activating an analog feedback gain within the modulators. This is accomplished by inserting a multiplexer and a 2X analog buffer in the feedback loop, which chooses between the unity and scaled-by-two magnitude of voltage value.

III. NON-UNIFORM OVERSAMPLING BEAMFORMER

In the proposed oversampled noise shaping beamformer dynamic focusing is achieved through using a Sampling Clock Generator (SCG) which dynamically delays the sampling clocks corresponding to the propagation time delays for successive focal points [16] (cf. Fig. 3). The SCG generates non-uniform sampling clocks, most effectively, by simply reading the beamforming delay patterns stored in a digital memory at a uniform master clock rate f_m. In non-uniform sampling scheme, the delay quantization error is determined by the timing resolution of the sampling clocks [4]. Thus a high speed master clock frequency f_m is needed to appropriately delay the echo signals, while the beamforming frequency f_{BF} is chosen only to satisfy the Nyquist condition of the pulse echo signals.

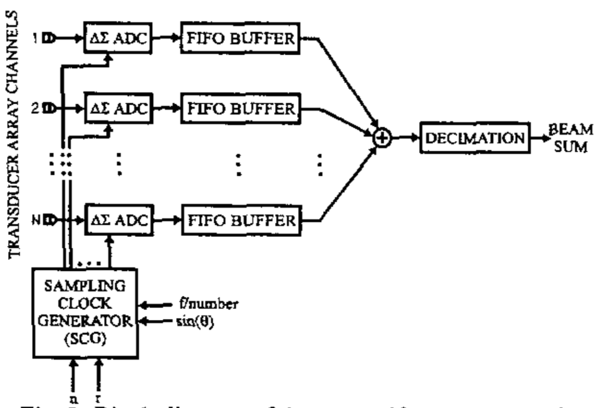

Fig. 3: Block diagram of the non-uniform oversampling beamformer

In the case of non-uniform oversampling beamformer, however, dynamic focusing should be performed at a very fast rate. Conventionally using a master clock rate f_m equal to f_{BF} results in signal resampling as delay patterns for some consecutive focal points are coincided on the same time resolution cell (cf. Fig. 2). In this context, the choice of f_m is of great importance to achieve a high performance ΔΣ beamformer. We have previously shown that there is a compact formula relating the minimum master clock rate to beamforming frequency in order to resolve the repeated samples in the delay structure and it is given by [7]:

$$\frac{f_m}{f_{BF}} \geq \frac{8 f_{num}^2}{8 f_{num}^2 - 1} \qquad (1)$$

where f_{num} is the f/number apodization constant employed in receive beam formation. The actual relationship between f_m and f_{BF} is dependent on many imaging parameters such as the range of the first focal point, array length and the distance between adjacent focal points. However, theoretical derivations and computer simulations presented in [7] have shown that the compact formula dependent on only f_{num} is working as intended. In the case of an exemplary f/number apodization of *2* (i.e., $f_{num}=2$), f_m must be selected at least *1.04* times the beamforming frequency f_{BF} corresponding to a very slight increase in the operation frequency of ΔΣ modulators, and thereby does not involve any significant hardware overhead.

Fig. 4 illustrates a simplified functional block diagram of SCG including a beamforming timing memory, a pattern generation logic and a set of logical "and" gates. The beamforming timing memory is a two dimensional (2-D) matrix whose columns and rows represent beamforming sampling times according to f_{BF} associated with f_m and index of the array elements, respectively. Each column includes "1"s and "0"s where "1"s denote the needed beamforming samples. The generation of non-uniform clocks is accomplished by simply performing a logical "and" operation between the content of the beamforming timing memory and the uniform master clock frequency f_m as described in [4].

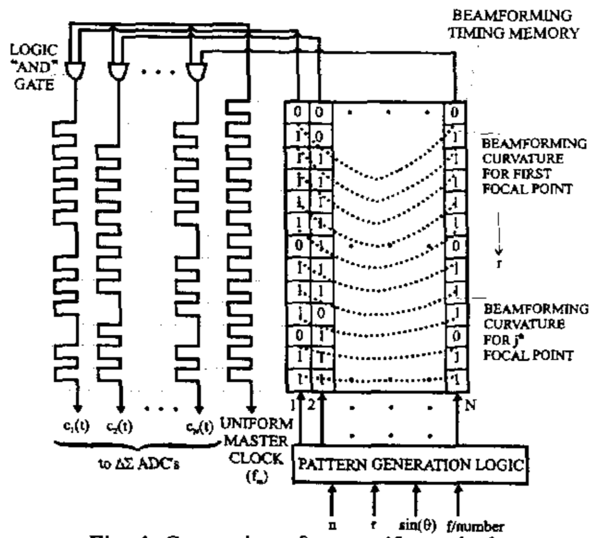

Fig. 4: Generation of non-uniform clocks

One bit coded echo samples appearing at different time instances are aligned through the FIFO buffer at each channel and piped out to summer node simultaneously to compose a coarse beam sum which consists of the summation of delayed echo signals along with some high frequency quantization noise. The coarse beam sum is then processed by a decimation filter to cut-off the high frequency noise injected by ΔΣ modulators and to reduce the sampling rate to the Nyquist rate.

IV. EXPERIMENTAL ANALYSIS

The image characteristic of the proposed system is investigated by means of emulations. In the experimental studies, we used rf data acquired from a phantom containing six nylon wires in a water tank to assess the point spread function (PSF) at different lateral and axial positions. This data was collected using a commercial *128*-element *3.5* MHz transducer array with half wavelength element pitch connected to a 10-bit A/D converter [6].

Dynamic focusing running at *222* MHz (f_{BF}=*222* MHz) was carried out on rf data, wherein an f/number apodization of *2* (f_{num}=*2*) was also employed during receive beam formation. It should be also noted that in emulations of oversampled noise shaping beamformers, an ideal software simulation model of the 2nd order single-bit ΔΣ modulator depicted in Fig. 5, was incorporated on each channel to digitize incoming echo signals.

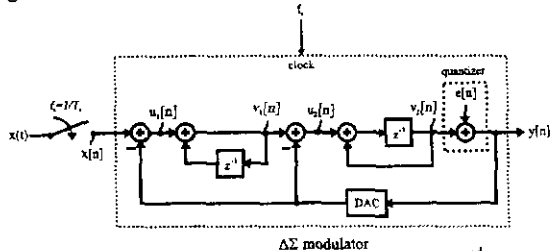

Fig. 5: Linearized sampled data model for 2nd order modulator

Fig. 6 demonstrates B-scan images of wire phantom for various beamforming approaches over *70* dB display range. The results of dynamic receive focusing using traditional 10-bit A/D converters is presented in panel (a). The image in panel (b) was reconstructed using the conventional single-bit ΔΣ beamformer architecture. Although the wires are perceptible over a snowy background noise, the noise level is worsened approximately by *20* dB. This unexpected noise is primarily due to the signal resampling resulting during dynamic focusing and limits the ultimate use of these kind of beamformers in clinical settings [6].

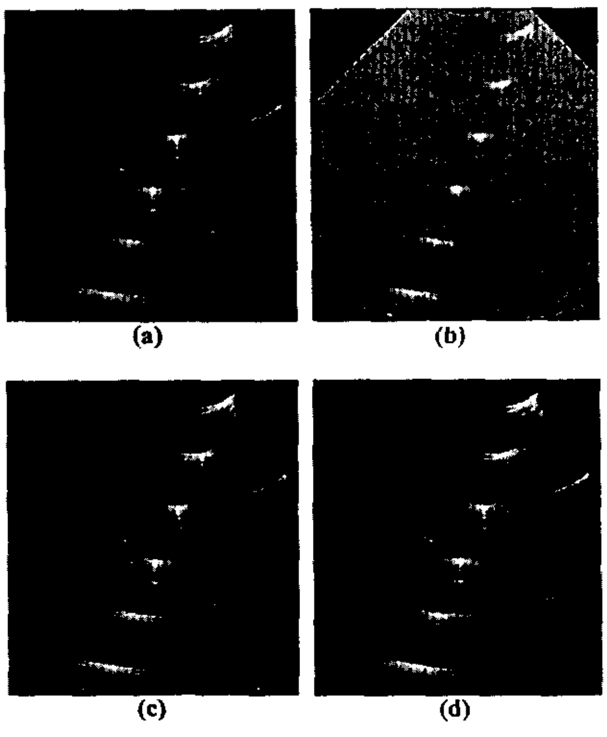

Fig. 6: B-Scan images of wire phantom

Dynamic focusing images generated by using single-bit ΔΣ beamformers employing 2X buffer compensation method [6] and the proposed non-uniform sampling approach are documented in panel (c) and (d), respectively. In both of the images, PSF's at six wires are nearly equivalent to those of 10-bit beamformer and the acoustic artifacts near third and fourth wires are also visible. The residual noise in these images is solely due to ΔΣ noise shaping performance, which can be improved either by using a higher order modulator and/or increasing the *OSR* and/or internal quantization bit count [7].

V. CONCLUDING REMARKS

A novel dynamically focused phased array beamformer based on non-uniform oversampled noise shaping conversion has been proposed. In this approach, only the echo samples that are required for receive beam formation are digitized by using a set of single-bit ΔΣ modulators, and the beam sum is obtained by synchronizing and summing the modulated bits across the array followed by a decimation process

In the proposed approach, one important point among the various design parameters, however, is the choice of master clock frequency f_m, which determines the time delay resolution of dynamic focusing. By using a minimum master clock frequency f_m, the signal resampling problem during dynamic focusing is completely avoided, so that the nodes of modulators are matched with those of the demodulator.

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