Orthogonal Frequency Division Multiplexing Combined with Multi Line Transmission for Ultrafast Ultrasound Imaging: Experimental

Orthogonal Frequency Division Multiplexing Combined with Multi Line Transmission for Ultrafast Ultrasound Imaging: Experimental Findings

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***Abstract*—Multi line transmission (MLT) and orthogonal frequency division multiplexing (OFDM) are techniques that have been individually applied to increase ultrasound imaging data acquisition rate. For both modalities, generating multiple beams in the transmit phase comes at the cost of image quality. In particular, interbeam cross-talk results in imaging artifacts, the intensity of which increases with the number of beams transmitted in parallel. In this study, we investigated experimentally whether and how the combination of MLT and OFDM could be used to achieve a high number of parallel beams with reduced cross-talk with respect to their individual use. Ultrasound images of wire targets and of a tissue-mimicking phantom have been acquired and analyzed for different configurations, i.e., with 2 to 6 beams transmitted in parallel. Imaging features such as the contrast ratio, contrast to noise ratio, axial resolution, and interbeam cross-talk have been evaluated. In conclusion, combining MLT and OFDM is effective to achieve a high data acquisition rate with limited cross-talk and higher CNR, with the drawback of reduced axial resolution and slightly diminished CR.**

Keywords—parallel beam forming, ultrafast ultrasound imaging, multi line transmission, orthogonal frequency division multiplexing

I. Introduction

Recently, orthogonal frequency division multiplexing (OFDM) and multi line transmission (MLT) beam forming have been shown capable of increasing the data acquisition rate of ultrasound imaging by transmitting multiple focused beams in parallel [1-8]. Differently from multi line acquisition (MLA) [9-11] and defocused wave imaging [12-16] these techniques make use of narrow focused beams in transmission. This allows generating ultrasound fields with higher pressure-amplitude values compared to the unfocused case, thus increasing the signal to noise ratio and the penetration depth. Moreover, this is particularly useful for harmonic imaging, where high pressure-amplitude is essential for the generation of the harmonic components [17]. For both MLT and OFDM, increasing the number of parallel beams, and thus the data acquisition rate, results in image artifacts (due to interbeam cross-talk), and deteriorates the image quality compared to standard (line by line) beam forming. To minimize the cross-talk, OFDM allocates each transmitted beam to a sub-band of the available bandwidth [2, 3, 7]. In the receive phase, the echoes generated by the different beams can then be identified and separated by means of band pass filters. Differently, in transmission, MLT optimizes the spatial distribution of the transmitted beams [4, 5, 6, 8], while, in reception, several methods have been proposed in literature to limit cross-talk artifacts: Tukey's window apodization [6,8], adaptive apodization [18], minimum variance beamforming [19], and Filtered-Delay Multiply And Sum beamforming [20].

In this study, we investigated experimentally whether and how the combination of MLT and OFDM could be used to achieve a high number of parallel beams with reduced cross-talk. In Section II the methodology utilized for this study is described. In Section III the results are presented. Conclusions can then be found in Section IV.

II. Methodology

90°-wide sector images, consisting of 144 lines, of wire targets and of the 040GSE phantom (Cirs Inc, Norfolk, VI, USA) were generated using the ULAOP 256 system [21, 22] equipped with a 2.4 MHz phased array (SP2430, Esaote, Firenze, Italy). Different configurations were tested, with 2, 3, 4, 6 simultaneously transmitted beams. Both standard wideband bursts and OFDM pulses with 2 or 3 different sub-bands were used. The latter were centered at 1.8 and 3 MHz, and at 1.6, 2.4 and 3.2 MHz, respectively; while the wideband burst was centered at 2.4 MHz and covered the entire 80% transducer bandwidth. In these experiments, the improved data acquisition rate was spent to increase the frame rate. Hence, at the maximum pulse repetition frequency (PRF) of 5 kHz and for an imaging depth of 15 cm, the frame rates for the described setups were respectively 70, 105, 140 and 210 Hz. Radiofrequency (RF) signals were beamformed in real-time and acquired for post-processing. Wire targets data were used to evaluate the -12 dB axial resolution and the inter beam cross-talk. The latter was measured as the ratio between the (highest) maximum image intensity of the "ghost wire" and the maximum image intensity of the actual wire. This measure was performed, for each configuration, as the average value over three wires placed at a depth of 2, 4 and 6 cm respectively. Similarly, the results presented for the axial resolution were also obtained by averaging over the results achieved for the three wires.

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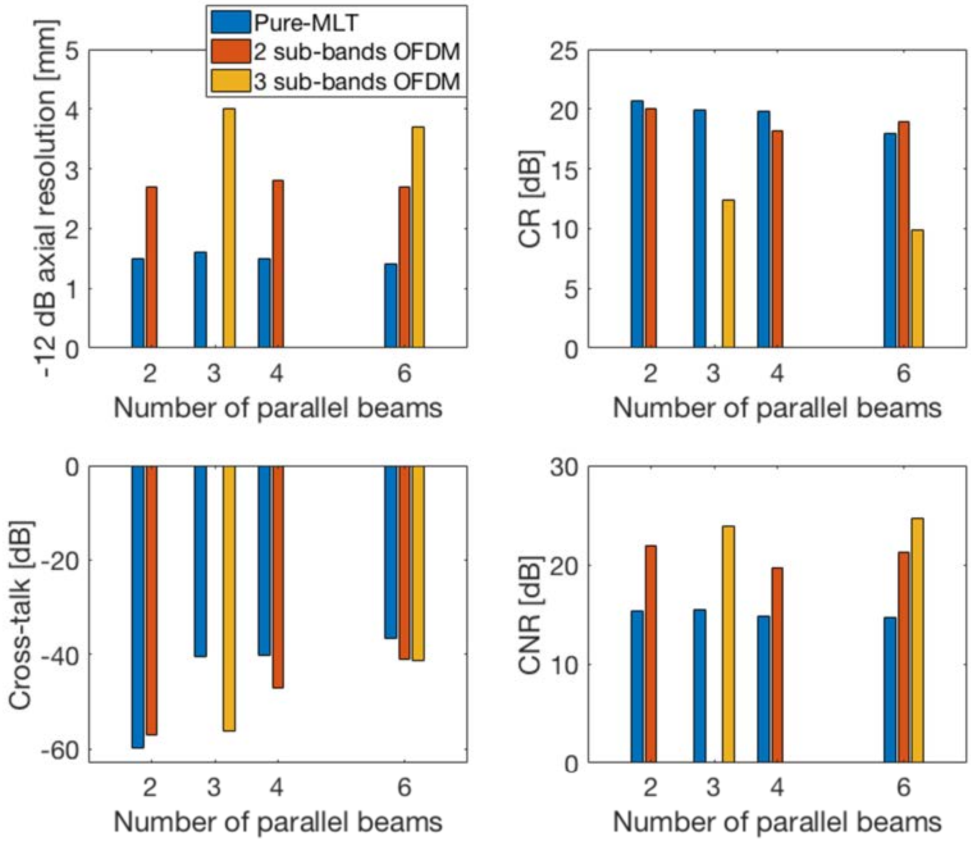

Fig. 1 Bar-plots presenting the results obtained. The -12 dB axial resolution (top-left), contrast ratio (top-right), cross-talk (bottom-left), and contrast to noise ratio (bottom-right) as achieved with 2, 3, 4, and 6 parallely transmitted beams are shown. Yellow bars are used to present the results for pure-MLT. Red and blue bars are used to present the results obtained when OFDM is implemented, with 2 and 3 sub-bands respectively.

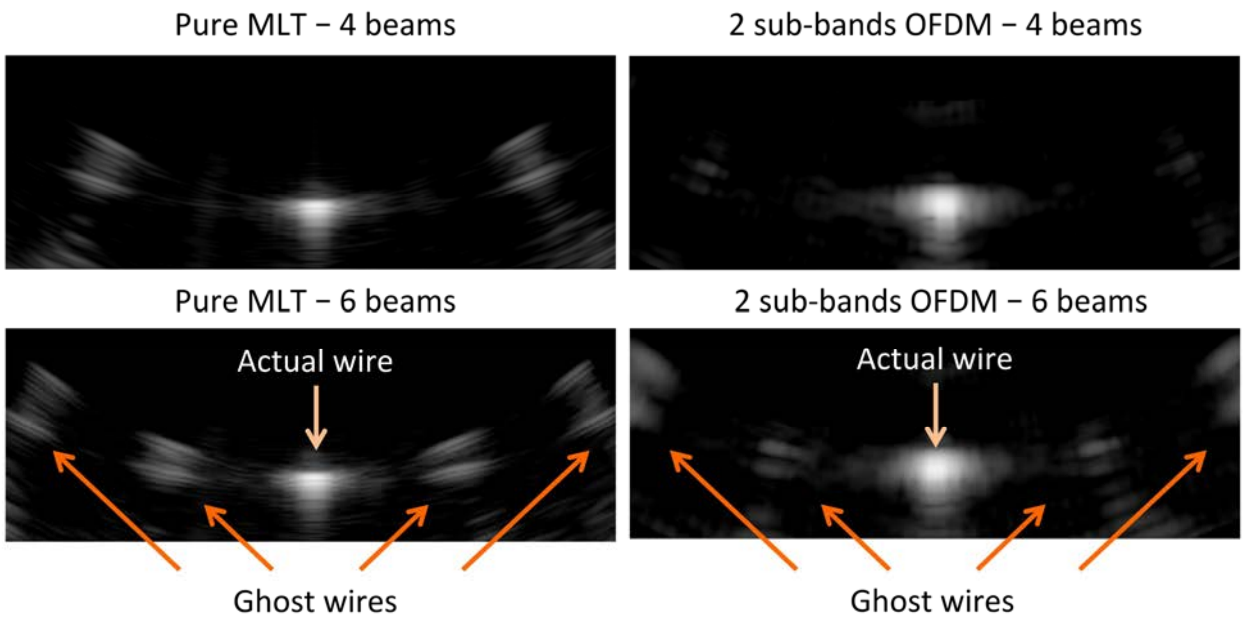

Fig. 2 Ultrasound images of the wire at a depth of 6 cm. The dysplayed normalized image intensity values are from 0 to -70 dB, for each image. Pure MLT (left) and OFDM (right) images are shown for a 4 (top) and 6 (bottom) beams configuration. As an example, the position of the actual wire, as well as the position of the ghost wires, is indicated by arrows in the bottom images.

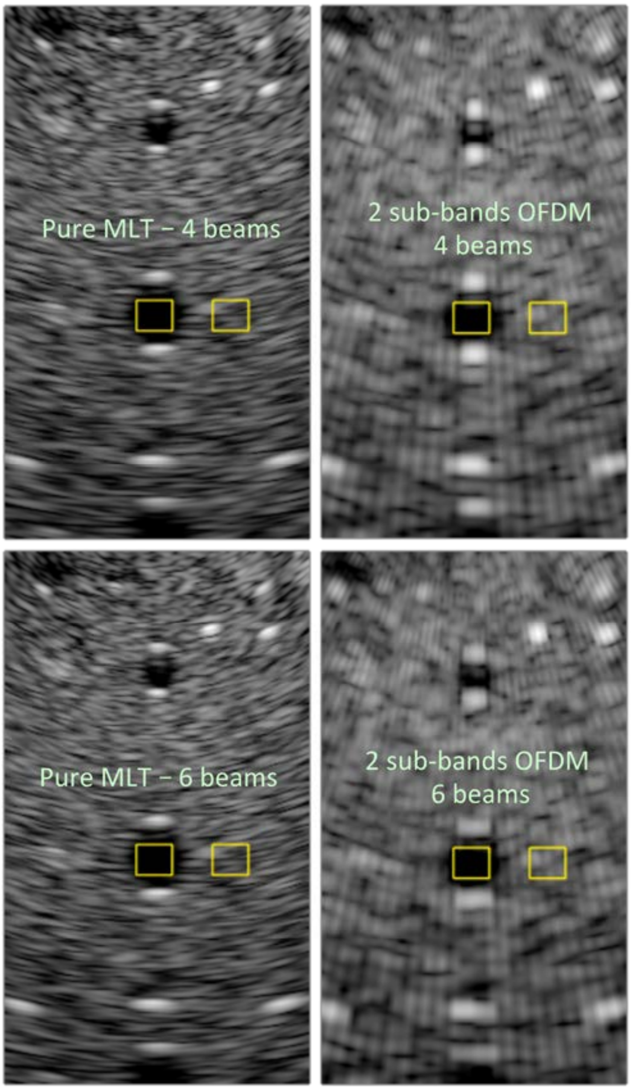

Fig.. 3 Ultrasound images of the tissue mimicking phantom. The displayed normalized image intensity values are from 0 to -40 dB, for each image. Pure MLT (left) and OFDM (right) images are shown for a 4 (top) and 6 (bottom) beams configuration. The areas used to evaluate CR and CNR are indicated by yellow boxes.

The images obtained from the tissue-mimicking phantom were used to assess contrast ratio (CR) and contrast to noise ratio (CNR).

$$\mathrm{CR} = \frac{\int_{C_{ROI}} dS}{\int_{S_{ROI}} dS} \cdot \frac{\int_{S_{ROI}} |IQ(S)|^2 \, dS}{\int_{C_{ROI}} |IQ(S)|^2 \, dS}$$

$$\mathrm{CNR} = \frac{2 \cdot \left(\mu_{S_{ROI}} - \mu_{C_{ROI}}\right)^2}{\sigma_{S_{ROI}}^2 + \sigma_{C_{ROI}}^2}$$

where $\mu_{S_{ROI}}$ and $\mu_{C_{ROI}}$ are the average amplitude values in S_{ROI} and C_{ROI} (see Fig. 3), respectively, while $\sigma_{S_{ROI}}$ and $\sigma_{C_{ROI}}$ represent the standard deviations.

III. Results

Figure 1 summarizes the results. Generally, combining OFDM with MLT allows reducing the cross-talk intensity and to increase CNR, as compared to pure MLT when the same number of parallel beams is transmitted. On the other hand, the use of OFDM negatively impacts the axial resolution. CR, in case two sub-bands are used, is essentially unchanged. In contrast, when three sub-bands are employed CR is negatively affected. As an example, combining MLT with 2 sub-bands OFDM to achieve 6 parallel beams, improved CNR (21.3 dB vs 14.7 dB), cross-talk rejection (41.0 dB vs 36.7 dB) and CR (18.9 dB vs 18.0 dB) compared to pure 6MLT, but worsened the axial resolution (2.7 mm vs 1.4 mm).

Figure 2 shows, as an example, 4 ultrasound images of the wire target positioned at a depth of 6 cm. The dynamic range of the displayed images is 70 dB. As can be seen for both the 4 and 6 parallel beams implementations, the combination of MLT and OFDM significantly reduces the intensity of the "ghost wires" (generated due to interbeam cross-talk) while worsening the axial resolution.

Figure 3 shows, as an example, 4 ultrasound images of the tissue mimicking phantom at a 40 dB dynamic range. The areas used to evaluate the CR and CNR values are indicated by yellow boxes. From figure 3 it is visible how OFDM changes the image appearance. The image becomes 'smoother' because longer pulses are utilized (explaining the higher CNR), and has a stripe pattern (due to adjacent lines being formed with a different center frequency). The latter effect can be compensated using spatial filtering [7].

IV. Conclusions

In this study, we proposed to combine MLT with OFDM to limit cross-talk artifacts when high numbers of parallel beams are employed. Preliminary experimental results showed that combining MLT and OFDM is effective to achieve a high data acquisition rate with limited cross-talk and higher CNR, with the drawback of reduced axial resolution and slightly diminished CR.

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