A compressed sensing approach for ultrasound imaging

Adrien Besson†, Rafael E. Carrillo⋆, Dimitris Perdios†, Marcel Arditi†, Yves Wiaux‡, Jean-Philippe Thiran†*

†Signal Processing Laboratory (LTS5), École Polytechnique Fédérale de Lausanne, Lausanne, Switzerland

⋆Centre Suisse d'Electronique et de Microtechnique (CSEM), Neuchâtel, Switzerland

‡Institute of Sensors, Signals, and Systems, Heriot-Watt University, Edinburgh, United-Kingdom

*Department of Radiology, University Hospital Center (CHUV) and University of Lausanne (UNIL), Lausanne, Switzerland

Introduction and objectives

1. Ultrasound (US) imaging uses multiple piezo-electric elements to transmit and receive acoustic pulses
2. Time-domain beamforming techniques require sampling rates ranging from 3 to 10 times the center frequency to minimize the delay-quantization errors
3. Such sampling rates may not be achievable in challenging environment, *e.g.* portable devices
4. We present a **compressed-sensing-based US acquisition and reconstruction approach**

Notations and model

- Notations:
  - 1D probe composed of N_{el} transducer elements located at $\boldsymbol{r}_i$
  - $m_i(t)$ signal received at i^{th} element
  - $\psi(t) = (e * h_{Tx} * h_{Rx})(t)$ elementary waveform
    - $e(t)$ excitation
    - $h_{Tx}(t)$ impulse response in transmit
    - $h_{Rx}(t)$ impulse response in receive
  - Medium composed of K inhomogeneities located at $\boldsymbol{r}_k$ and with reflectivity $\gamma(\boldsymbol{r}_k)$

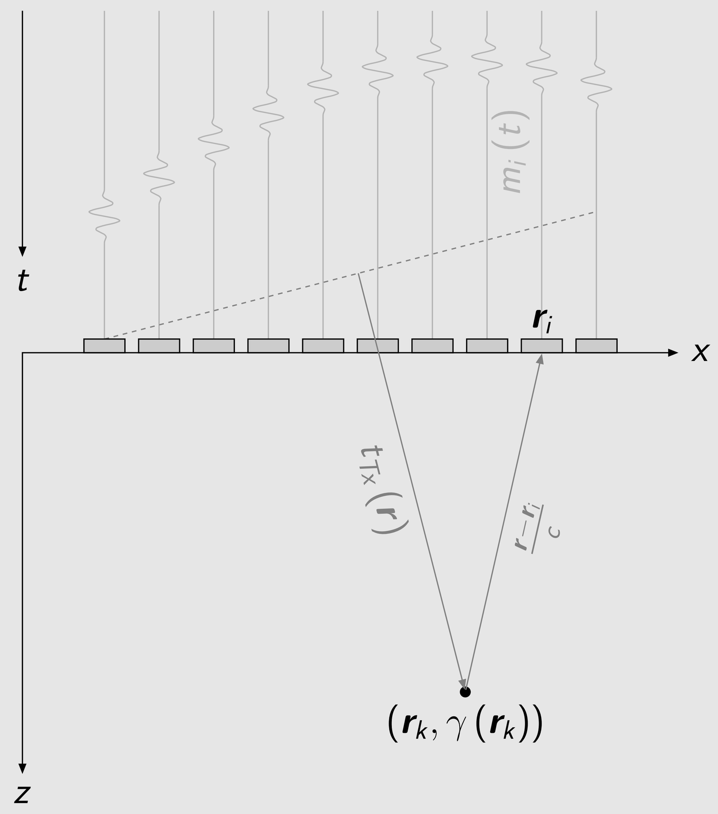


Figure Standard setting for US imaging

- The signals received at each element follow a **stream of pulses** model and can be written as:

$$m_i(t) = \sum_{k=1}^{K} a_{ik}\psi(t - t_k)$$

with $(a_{ik}, t_k)_{k=1}^{K}$ amplitudes and times-of-arrival of the K echo-pulses to the i^{th} transducer-element

- The N_t discretized samples obtained by sampling $m_i(t)$ at a frequency f_s **obey a** K**-sparse synthesis model** in a dictionary $\Psi \in \mathbb{R}^{N_t \times N_t}$ made of all the shifted replicas of the pulse [1]:

$$\boldsymbol{m}_i = \Psi \boldsymbol{a}_i, \text{ with } \|\boldsymbol{a}_i\|_0 = K$$

The proposed acquisition scheme: US compressive multiplexer

- **CMUX** [2]: Signals from M sensors are modulated and summed:

$$y(t) = \sum_{i=1}^{M} p_i(t)\, m_i(t)$$

where $p_i(t)$ is a chipping sequence drawn from a Rademacher distribution

- Signal $y(t)$ sampled at f_s leading to a compression by a factor of M
- **US-CMUX**: Use L CMUX each of which grouping M sensors and sharing the same chipping sequences to perform signal acquisition

$$\mathrm{Y} = [\boldsymbol{y_1}, ..., \boldsymbol{y_L}] \in \mathbb{R}^{N_t \times L}$$

- Compression by a factor of M compared to standard US devices
- Can be achieved using mixed signal blocks [2]

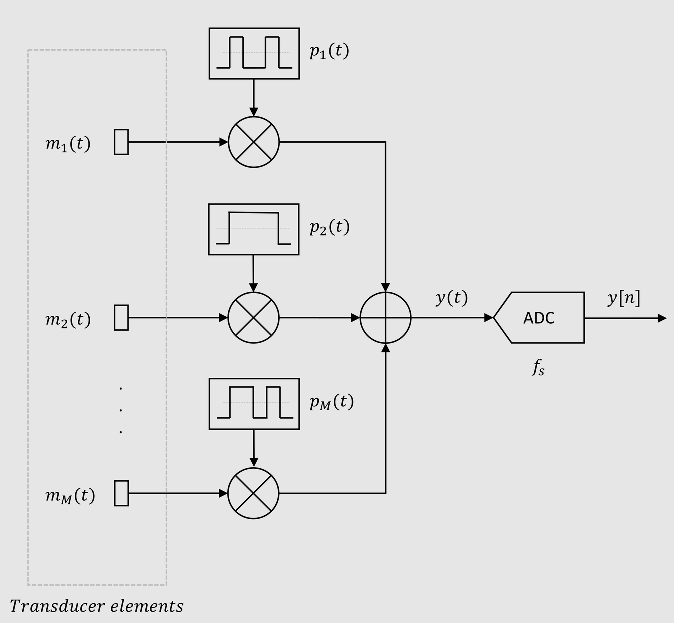


Figure CMUX architecture

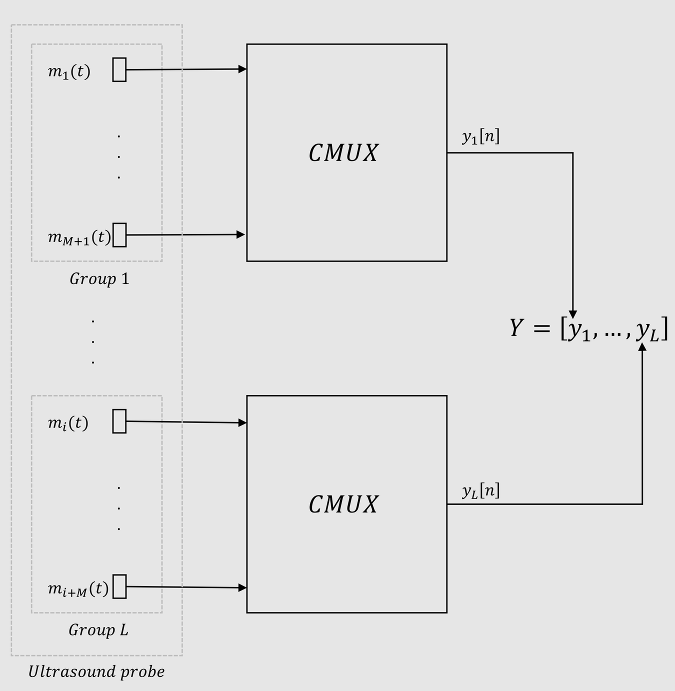


Figure US-CMUX architecture

Proposed reconstruction algorithm

- ℓ_{11}-minimization problem is solved:

$$\min_{\bar{\mathrm{A}} \in \mathbb{R}^{MN_t \times L}} \|\bar{\mathrm{A}}\|_{11} \text{ subject to } \|\mathrm{Y} - \Psi_P \bar{\mathrm{A}}\|_F \leq \epsilon$$

$$\Psi_P = [\Psi_{p1}, ..., \Psi_{pM}] \in \mathbb{R}^{N_t \times MN_t},\ \Psi_{pi} = [\boldsymbol{p}_i \otimes \Psi_1, ..., \boldsymbol{p}_i \otimes \Psi_{N_t}] \in \mathbb{R}^{N_t \times N_t}$$

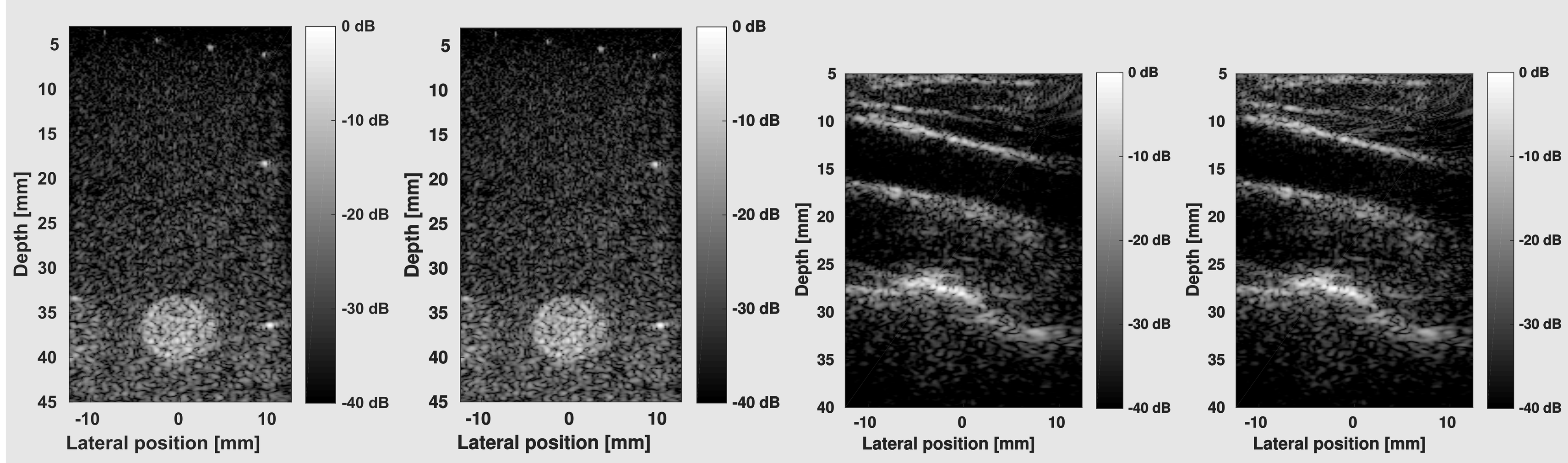
$$\mathrm{A} = \begin{bmatrix} \boldsymbol{a}_1 & \boldsymbol{a}_{M+1} & \cdots & \boldsymbol{a}_{N_{el}-M+1} \\ \vdots & \vdots & & \vdots \\ \boldsymbol{a}_M & \boldsymbol{a}_{2M} & \cdots & \boldsymbol{a}_{N_{el}} \end{bmatrix}$$

- Solved with primal dual forward backward algorithm [3]

Experimental setup

- Data acquisition:
  - *In-vitro* hyperechoic inclusion phantom (Model 54GS, CIRS Inc., Norfolk, USA) and *in-vivo* carotids
  - Data acquired with a Verasonics research scanner (V1-128, Verasonics Inc., Redmond, WA)
  - ATL L12-5 50 mm ultrasound probe used for the different experiments
    - 128 active transducer-elements
    - 5 MHz central frequency with 100 % bandwidth
    - 31.2 MHz sampling frequency
  - Transmission of plane waves with normal incidence
- US-CMUX architecture
  - Simulated on MATLAB®
  - 2 cases: L=2 and L=4
  - Parameters of the reconstruction algorithm: $\epsilon = 10^{-6}\|\mathrm{Y}\|_F$, 1500 iterations
- Image reconstruction:
  - Achieved with standard delay-and-sum algorithm
  - Post-processing pipeline for B-mode image
    - Envelope extraction: Hilbert transform
    - Normalization and log-compression with a dynamic range of 40 dB

Reconstructed B-mode images



(a) Reference (b) CS reconstruction (c) Reference (d) CS reconstruction

Figure B-mode images of the hyperechoic inclusion and the carotid reconstructed with 100 % of the data ((a) and (c)) and with 25 % of the data acquired with US-CMUX ((b) and (d))

Quality metrics of the reconstructed images

- PSNR and SSIM against B-mode images reconstructed with 100 % data

Table Average PSNR [dB] and SSIM [−] over 10 draws for the different images

	Hyperechoic inclusion	*In-vivo* carotid
PSNR - $L = 2$	39	36
SSIM - $L = 2$	0.94	0.87
PSNR - $L = 4$	32	29
SSIM - $L = 4$	0.81	0.72

- High quality reconstruction with 25 % of the data.

Conclusion and perspectives

1. We propose a compressed sensing approach for US image recovery
   - Exploits a stream of pulses model for sparsity of US images
   - Uses multiple CMUX for analog compression of the data
   - Applies a ℓ_{11}-minimization algorithm for image reconstruction
2. The proposed approach leads to high-quality reconstruction with far fewer data than standard approaches
3. Study of the hardware implementation will be achieved in future work

References

[1] F. M. Naini, R. Gribonval, L. Jacques, and P. Vandergheynst, "Compressive sampling of pulse trains: Spread the spectrum!", in *2009 IEEE Int. Conf. Acoust. Speech Signal Process.*, 2009, pp. 2877–2880.

[2] Y. Kim, W. Guo, B. V. Gowreesunker, N. Sun, and A. H. Tewfik, "Multi-channel sparse data conversion with a single analog-to-digital converter", *IEEE J. Emerg. Sel. Top. Circuits Syst.*, vol. 2, no. 3, pp. 470–481, 2012.

[3] P. L. Combettes, L. Condat, J.-C. Pesquet, and B. C. Vu, "A forward-backward view of some primal-dual optimization methods in image recovery", in *2014 IEEE Int. Conf. Image Process.*, 2014, pp. 4141–4145.

Acknowledgments

This work was supported in part by the UltrasoundToGo RTD project (no. 20NA21 145911), evaluated by the Swiss NSF and funded by Nano-Tera.ch with Swiss Confederation financing.The authors would like to thank Dr Olivier Bernard from CREATIS laboratory for providing the *in vitro* and *in vivo* acquisition data.