Time Reversal for wireless communications

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Multidisciplinary approach of wave physics

All kinds of waves: Acoustics, Water waves, Microwaves, Optics

Ultrasound

Microwave

Spatial shaping

Temporal shaping

Interferometry (detection)

Optics

Liquid crystals SLM

Femtosecond Coherent control

holography

Time-resolved techniques
Interplay between fundamental physics and applications

- Anderson localization,
- Random lasers,
- QED,
- Wave chaos,
- Random Matrix Theory

- Medicine and Biology,
- Non destructive testing,
- Wireless communications,
- Defense industry,
- Geophysics,...
Innovation and start-up companies

- **ECHOSENS** (2001)
  50 employees *(Mongolia Pharm)*
  > 2000 Fibroscan sold

- **SENSITIVE OBJECT** (2003)
  35 employees *(Tyco)*

- **SUPERSONIC IMAGINE** (2005)
  120 employees
  > 800 Aixplorer sold

- **TIME-REVERSAL COM** (2008)
  40 employees *(Bull)*

- **LLTECH** (2008)
  8 employees
- Time reversal focusing of ultrasound in multiple scattering media
- Time Reversal for communication purposes
- Time Reversal vs Inverse Filter
- Time Reversal of microwaves
- Time Reversal and super-resolution
\[ p(\vec{r}, t) \] is the acoustic pressure field (scalar)
\[ \rho(\vec{r}) \] is the density and \( c(\vec{r}) \) is the sound velocity

Time Reversal

\[ \rho(\vec{r}) \text{div} \left( \frac{\text{grad}(p)}{\rho(\vec{r})} \right) - \frac{1}{c^2(\vec{r})} \frac{\partial^2 p}{\partial t^2} = 0 \]

Linear acoustics
No loss

This equation contains only \( \frac{\partial^2 p(\vec{r}, t)}{\partial t^2} \)

Then if \( p(\vec{r}, t) \) is a solution
\( p(\vec{r}, -t) \) is also a solution

because \( \frac{\partial^2 p(\vec{r}, t)}{\partial t^2} = \frac{\partial^2 p(\vec{r}, -t)}{\partial t^2} \)
A wave is sent out from a source, propagates, is captured by a set of receivers and flipped in time. The resulting *time-reversed wave* propagates back and converges at the initial source location.

D. Cassereau, M. Fink (1992)
Time Reversal in multiple scattering media

Single transducer
\( f = 3.2 \text{ MHz}, \lambda = 0.48 \text{ mm} \)

2D random sample

MRT
128-transducer array
Pitch: 0.42 mm
TR in multiple scattering media: temporal compression

Beamwidth at -12 dB: 1 mm (scattering medium) / 35 mm (free space)

➔ The hyperfocusing effect

Experiments have also been carried out with the same scatterers periodically distributed (PC’s)
➔ No hyperfocusing effect

Time-reversal in multiple scattering media

Directivity patterns of the time-reversed waves

Spatial degrees of freedom ↔ Temporal degrees of freedom

A. Derode, A. Tourin and M. Fink, Phys. Rev. E 64, 036606 (2001)
Time-reversal in multiple scattering media

\[ p(\vec{r},t) \iff p(\vec{r},-t) \]
\[ P(\vec{r},\omega) \iff P^*(\vec{r},\omega) \]
The peak to sidelobes ratio is expected to vary as

\[
\sqrt{\frac{\Delta \omega}{\delta \omega}} = \sqrt{\frac{\tau_{th}}{\Delta t_p}}
\]
Time Reversal in multiple scattering media

Field-field correlation \( \langle \Psi(\omega)\Psi^*(\omega + \omega') \rangle \) = Fourier transform of the TOF \( \langle I(t) \rangle \)

\[ \tau_{th} \approx \frac{L^2}{D} = 150 \mu s \quad \delta \omega = 8 \text{kHz} \quad \Delta \omega / \delta \omega = 150 \]
Time Reversal in multiple scattering media

Coherent control over spectral (temporal) and spatial degrees of freedom

\[ \propto \sqrt{N_\omega N_S} \]

\( N_S \) Number of spatial degrees of freedom (transducers, antennas)

\( N_\omega \) Number of temporal / spectral degrees of freedom

\[ \sqrt{\Delta \omega / \delta \omega} = \sqrt{\tau_\text{th} / \Delta t} \]
Time Reversal for communication purposes

Time Reversal compensates for reverberation (equalization)
MIMO-MU (Multiple Input - Multiple-Output Multi Users) scheme

Distance 27 cm (~ 600 $\lambda$)

23-transducer array

Frequency: 3.2 MHz ($\lambda$~0.5 mm)

5 users

40 mm

Time Reversal for communication purposes

Random series of 2000 bits

<table>
<thead>
<tr>
<th></th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>Error rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest of rods</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>10^-4</td>
</tr>
<tr>
<td>Water</td>
<td>489</td>
<td>640</td>
<td>643</td>
<td>602</td>
<td>503</td>
<td>29%</td>
</tr>
</tbody>
</table>
Time Reversal for communication purposes

**SISO communication**:
$$\log_2(1 + S / N) \text{ bits/s/Hz} \quad (Shannon, 1948)$$

**MIMO communication**:
$$\max_Q \left\{ \text{Tr} \left[ \log_2 \left( \ln R + \frac{1}{N} HQ^i H^* \right) \right] \right\} \text{ bits/s/Hz}$$


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Free space (water)

Multiple scattering medium

40 × 40 channel matrix

@ 3.2 MHz (threshold –32 dB) : 34 / 6 singular values (eigenvalues of the TR operator)
Time Reversal for underwater communications

3.5 kHz, \( \lambda = 50 \text{ cm} \)

B. Kuperman’s group
Scripps, San Diego

\[ L = 78 \text{ m} \]
\[ N = 29 \]

\[ 3.5 \text{ kHz}, \lambda = 50 \text{ cm} \]
Time Reversal for underwater communications

Experiment conducted near Elba island

P. Roux, B. Kuperman
Time Reversal for underwater communications

Training step

Time reversal

Time reversal communications
Time reversal vs inverse filter

\[ H(\omega) \]

\[ N \times N \text{ transfer matrix} \]

\[ H^{-1}F = E \]

\[ f_m(t) = \sum_{j=1}^{N} h_{mj}(t) \otimes e_j(t) \]

\[ F(\omega) = H(\omega)E(\omega) \]

\[ F = (0, \ldots, 0, 1, 0, \ldots, 0) \]
Time reversal vs inverse filter

$H F$

$H$

$m$

$F = {}^t(0, ..., 0, 1, 0, ..., 0)$

Time reversal vs inverse filter

$H^* F^*$

$^tH$

$^tH H^* F^*$

$^tH H^*$

$F$

$^tH^* H$ is the Time Reversal Operator
A spatial matched filter must maximize
\[ J(E) = \frac{\langle HEF \rangle}{\|E\|} = \frac{\langle E'H^*F \rangle}{\|E\|} \]

The Cauchy-Schwartz inequality gives an upper-bound on this expression
\[ \frac{\langle E'H^*F \rangle}{\|E\|} \leq \|H^*F\| \]

Equality holds when
\[ E = k(\omega)(H^*F)^* = k(\omega)\{H\}_m^* \]

Focusing is given by
\[ H(H^*F)^* = H^tH^*F \]
Time reversal as a temporal matched filter

\[ s(0) = \int |H(\omega)|^2 d\omega \]

\[ s(t) = h(t) \otimes h(-t) \]

TR is a temporal matched filter (linearity and reciprocity)
Inverse filter based on iterative time reversal

\[ i \in [1, M], \quad e_i(t) \]

M-antenna base station

\[ j \in [1, N], \quad o_j(-t) \]

N users

Temporal « Cross-talking »

Spatial « Cross-talking »

\[ e_i(-t) \]

\[ r_i(t) \]

Bit
Iterative time reversal

Basic idea: iterative suppression of the sidelobes

\[ d_j(-t) = o_j(-t) - r_i(-t) \]

Reconstruction of the sidelobes
Iterative time reversal

\[ e_i(-t) \]

\[ c_i(-t) \]

\[ e_j^2(-t) \]

\[ r_j^2(-t) \]

G. Montaldo, G. Lerosey, A. Derode, A. Tourin, J. de Rosny, M. Fink
Iterative Time reversal

15 users, $\tau=1.5$ ms, $\delta t=1.5$ $\mu$s

Original message (to user #5)

Reception using time reversal (MMSE)

Reception using iterative TR (MMSE)
Iterative Time reversal

\[ P_{\text{error}} = \frac{1}{2} \text{erfc} \left( \frac{1}{\sqrt{2(\sigma_{\text{int}} + \sigma_{\text{ext}})}} \right) \]

\[ \sigma_{\text{int}} = \sigma_{\text{int1}} \sqrt{N \tau / \delta t} \]

\[ \sigma_{\text{total}} = \sqrt{\sigma_{\text{int}}^2 + \sigma_{\text{ext}}^2} \]
Time reversal of microwaves @ 2.4 GHz


Impulse response in the cavity

- Original pulse: 10-ns long
- Estimated RMS delay spread: $\tau_{\text{RMS}} = 160$ ns

Time Reversal compression

- Original pulse recovered
- Compression amplitude gain: $G \sim \tau_{\text{RMS}}$
Spatial Focusing

- Security of transmission
- TR is a spatial multiplexer
- Spectral efficiency

Time reversal of microwaves

![Time Reversal Focal Spot](chart)

- 6 cm
Time reversal of microwaves and super resolution

Wavelength 12 cm @ 2.4 GHz

Details of one antenna

G. Lerosey, J de Rosny, A. Tourin, M. Fink
The TRM is made of 3 antennas
Central frequency : 2.45 GHz
Bandwidth : 180 MHz

3 bitstreams (RGB)
Data rate: 50 Mbits/s each
The global data rate is 150 Mbits/s

Time-Reversal Communications founded in 2008 (40 people)
Time reversal of microwaves and super resolution

Concluding remarks

Time-Reversal UWB Wireless Communication-Based Train Control in Tunnel

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Combining UWB with Time Reversal for improved communication and positioning

Luca De Nardis - Jocelyn Florina - Dorin Panaitopol - Maria Gabriella Di Benedetto

Time-Reversal Division Multiple Access over Multi-Path Channels

Feng Han, Student Member, IEEE, Yu-Han Yang, Student Member, IEEE, Beibei Wang, Member, IEEE, Yongle Wu, Member, IEEE, and K. J. Ray Liu, Fellow, IEEE

Green Wireless Communications: A Time-Reversal Paradigm

Beibei Wang, Member, IEEE, Yongle Wu, Feng Han, Student Member, IEEE, Yu-Han Yang, Student Member, IEEE, and K. J. Ray Liu, Fellow, IEEE