PHOTONICS APPLIED TO COHERENT RADAR NETWORKS FOR BORDER SECURITY

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OUTLINE

- Photonic Technology for Distributed Radar Networks
  - Challenges in Maritime Surveillance
  - Distributed Radar Networks (Decentralized vs Centralized)
  - Photonics for Distributed Radar Networks

- Maritime Surveillance in the Port of Livorno (Italy)
  - The NATO-SPS SOLE Project
  - Simulation of the Maritime Scenario
  - Detection Applied to a Distributed Radar
  - Preliminary Simulation Results

- Preliminary Photonics-Assisted Distributed Radar Network Architecture
  - Down-scaled System Architecture
  - Experimental Setup and Results

- Conclusions
PHOTONIC TECHNOLOGY FOR DISTRIBUTED RADAR NETWORKS
CHALLENGES IN MARITIME SURVEILLANCE

- **TASKS**
  - Detection
  - Tracking
  - Classification
  - Identification

- **AVAILABLE SENSORS**
  - Synthetic Aperture Radar (SAR) imagery
  - Automatic Identification System (AIS)
  - Very High Resolution (VHR) imagery
  - Coastal radars (e.g., HF, S, X bands)
  - etc...

- **CHALLENGES in RADAR SYSTEMS**
  - Target RCS fluctuations (up to 25dB!)
  - Sea clutter features (e.g., sea spikes)

- **POSSIBLE SOLUTIONS**
  - Multiband operation
  - Multisensor operation

**REFERENCE:**
DISTRIBUTED RADAR NETWORKS

DECENTRALIZED Radar Network
Multistatic Radar

- Local preprocessing at the slave nodes
- Fair-bandwidth links for signal distribution

CONS:
- Complex slave nodes
- Information from sensor fusion not truly maximized

CENTRALIZED Radar Network
Multiple-Input Multiple-Output (MIMO) Radar

- Maximization of information from sensor fusion

CONS:
- Time and phase synchronization
- Large-bandwidth links for signal distribution

HOWEVER...
Photonic technology allows to overcome these problems!

REFERENCE:
- Excellent phase stability in multiband signal up/down-conversion
- Preservation of phase stability upon signal distribution
- A single photonic core manages multiple distributed radar heads (Centralized Architecture)!

REFERENCE:
MARITIME SURVEILLANCE IN THE PORT OF LIVORNO (ITALY)
THE NATO-SPS SOLE PROJECT

Multistatic and Multiband Coherent Radar Fleet for Border Security

- Implementation/field trial of a multiband distributed MIMO radar network
- Optimization of target detection algorithms upon MIMO processing
- Fusion of 2D-ISAR images and 3D-ISAR imaging

The Project

http://www.sole-natosps.eu/
For each TX\textsubscript{k}-RX\textsubscript{l} radar pair (k=1,...,M and l=1,...,N), the e.m. scatterers within the target silhouette are extracted. For simplicity, we assume one e.m. scattering element at the crossing of each TX\textsubscript{k}-RX\textsubscript{l} range cell. Based on the point-like scatterers, the received signal at TX\textsubscript{k}-RX\textsubscript{l} can be generated:

\[ r_{k,l}(t) = \sum_{m=1}^{Ns} a_{k,l}^m s_k(t - \tau_{k,l}^m) e^{j[\theta_t(t) - \tau_{k,l}^m - \theta(t)]} + n_{k,l}(t) \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(s_k(t))</td>
<td>Signal transmitted by TX\textsubscript{k}</td>
</tr>
<tr>
<td>(a_{k,l}^m)</td>
<td>Amplitude factor</td>
</tr>
<tr>
<td>(\tau_{k,l}^m)</td>
<td>Delay due to bistatic distance</td>
</tr>
<tr>
<td>(n_{k,l}(t))</td>
<td>Additive white Gaussian noise (AWGN)</td>
</tr>
<tr>
<td>(Ns)</td>
<td>No. of scatterers seen by TX\textsubscript{k}-RX\textsubscript{l}</td>
</tr>
</tbody>
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**System Geometry**

**Extraction of scatterers**
Finally, the coherent MIMO cross-ambiguity function can be estimated in the 2D Cartesian space:

\[
\Lambda[r(t)] = c' \left| \sum_{k=1}^{M} \sum_{l=1}^{N} e^{-j2\pi f_c \tau_{k,l}} \int r_{k,l}^{BB^*}(t) s_k^{BB} (t - \tau_{k,l}) dt \right| + c''
\]

### Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Skiff length (L)</td>
<td>10 m</td>
</tr>
<tr>
<td>Number of TXs (N_{TX})</td>
<td>3</td>
</tr>
<tr>
<td>Number of RXs (N_{RX})</td>
<td>3</td>
</tr>
<tr>
<td>Waveform</td>
<td>LFM Chirp</td>
</tr>
<tr>
<td>Carrier frequency (f_c)</td>
<td>9.7 GHz</td>
</tr>
<tr>
<td>Bandwidth (B)</td>
<td>100 MHz</td>
</tr>
</tbody>
</table>

Spatial coherent MIMO processing allows to image the target!
Cell Averaging – Constant False Alarm Rate (CA-CFAR) Detection

Target detection is performed in the **cell under test** (CUT):

\[
Y > H_1 \quad \text{and} \quad Y < H_0 \quad T \cdot Z
\]

The CFAR criterion keeps the **probability of false alarm below a preset acceptable level**.

<table>
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<th>Symbol</th>
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</tr>
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<tbody>
<tr>
<td>(Y = \Lambda[r(t)])</td>
<td>Detection statistic</td>
</tr>
<tr>
<td>(H_1)</td>
<td>target present in the CUT</td>
</tr>
<tr>
<td>(H_0)</td>
<td>target absent in the CUT</td>
</tr>
<tr>
<td>(T)</td>
<td>Scale factor (deterministic)</td>
</tr>
<tr>
<td>(Z)</td>
<td>Noise power estimate</td>
</tr>
</tbody>
</table>

**How do we choose the training cells?**
PRELIMINARY SIMULATION RESULTS

Non-Coherent 3x3 MIMO Output

The number of false alarms due to sidelobes is reduced!

Rectangular Training Cells

Ellipsoidal Training Cells

Detection Outputs

false alarms!
PRELIMINARY PHOTONICS-ASSISTED DISTRIBUTED RADAR NETWORK ARCHITECTURE
PRELIMINARY SYSTEM ARCHITECTURE

Photonic 2x2 MIMO Radar Architecture

Radar network configuration:
- 2 radar transceivers
- Single-band @ 9.7 GHz
- 100 MHz bandwidth
- LFM chirp: PW 100 ns, PRI 50 μs

Fiber network configuration:
- One fiber pair for each RH
- Analog Radio-over-Fiber
- Bandwidth compatible with ITU

REFERENCE:
Targets:
- 2 cylinders in metal net, 50cm x 34cm Ø
- Suspended to small quad-copter drones, 15÷20m above the floor
- Distance between targets: ~3m
- Positions checked with GPS data from drone

EXPERIMENTAL SETUP

In-field trials on TeCIP roof

Target carried by the drone

1 km fiber
Non-Coherent vs Coherent 2x2 MIMO Results

Non-coherent MIMO

Coherent MIMO

Antennas HPBW ≈50°, target distance ≈18m → Cross-range Resolution: ≈15 m
Resolution Enhancement: 5x!
CA-CFAR Detection Results

CA-CFAR (rectangular training cells)

CA-CFAR (ellipsoidal training cells)

The coherent MIMO processing is capable of distinguishing the 2 targets. The proposed modified CA-CFAR approach allows to detect them and to mitigate the number of false alarms due to sidelobes!
The contribution of **photonic technology** is decisive for developing distributed centralized radar networks, due to the high level of coherence granted upon signal generation, reception and distribution.

A **distributed multiband photonics-assisted 3x3 MIMO radar system** will be operated in a real maritime surveillance scenario within the NATO-SPS SOLE Project.

In this work, a preliminary operative scenario has been considered. A simple methodology has been proposed to **simulate extended targets**, by extracting the main scattering elements observed by each bistatic TX-RX radar composing the distributed radar network.

A **modified version of the CA-CFAR detection strategy has been proposed** to cope with false alarms due to cross-range sidelobes in the MIMO cross-ambiguity function.

Moreover, **results of a preliminary down-scaled 2x2 MIMO system architecture working in an outdoor scenario have shown the potential of photonics-assisted MIMO radars**, in terms of enhanced cross-range resolution and target imaging capability.
THANK YOU VERY MUCH!
PhD student and post-doc positions are available
at Scuola Superiore Sant’Anna / CNIT in Pisa, Italy

If interested, please send an email to:

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