RADAR Emitter Classification with Optimal Transport Distances

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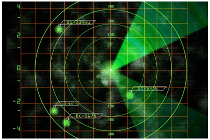
Contex

- Electronic intelligence is a challenging field
- Specifically RADAR Identification:
  - → Identifying the enemies gives a considerable advantage (decision-making, commitment ...)
  - → Anticipating the actions and setting up adapted measures
  - → Deal with complex environment



Actual methods

? Methods:

- → Time-frequency analysis: Kawalec, A., & Owczarek, R. (2004)
- → Deep learning: Lundén, J., & Koivunen, V. (2007) - Liu, Z. M., & Philip, S. Y., 2018 - Ding, L., Wang, S., Wang, F., & Zhang, W. (2018)

✘ Limits: Supervised methods, few classes, model retrained, performance depends on simulator accuracy...

➥ Our solution: Develop a new classification method based on optimal transport distance

Data acquisition

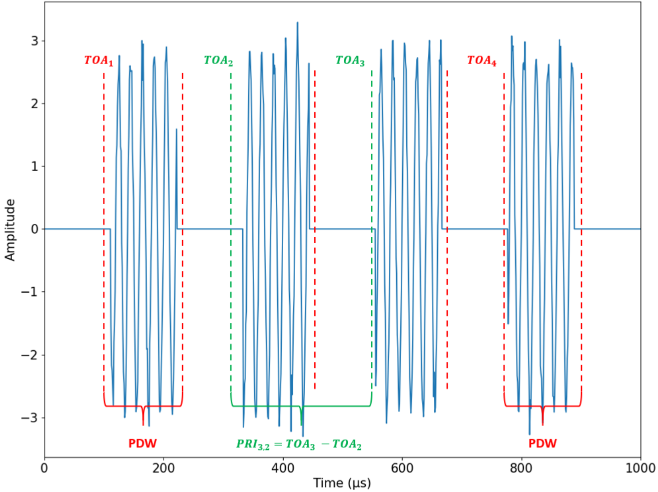


Figure: RADAR pulses acquisition example with 4 pulses trains.

Data description

- Work from simulated labeled data
- Each train is composed of RADAR pulses, described by only 4 features:

$$PDW_i = \begin{pmatrix} F_1 & PW_1 & L_1 & TOA_1 \\ F_2 & PW_2 & L_2 & TOA_2 \\ \vdots & \vdots & \vdots & \vdots \\ F_m & PW_m & L_{i,m} & TOA_m \end{pmatrix}$$

i = the train
m = pulses index

F = frequency
PW = pulse width

L = level
TOA = time of arrival

RADAR Signal example

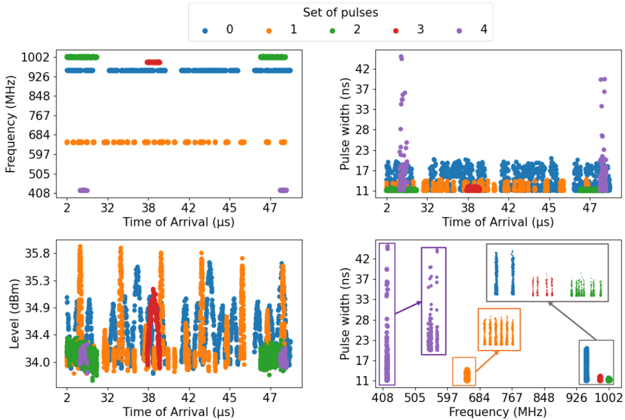


Figure: Example of a **simple** signal containing 5 RADARs. Each color represents a different emitter.

Requirement

Hypothesis: 1 set of pulses = 1 RADAR

Input: Deinterlaced sets of pulses obtained by a previous deinterlacing method

Deinterlacing RADAR signal

☛ Separation and grouping of mixed data from a RADAR signal containing data from an unknown number of RADARs

? Methods:

- → Pulse repetition intervals: Mardia (1989) - Milojevic & Popovic (1992)
- → Clustering: Kang & al (2022)
- → Deep Learning: Z. Liu & P. S (2018)
- → Optimal Transport: Mottier, Chardon & Pascal (2021)

Content

Emitter class description

- Database with more than 60 classes

$$EmitterClass_j = \begin{pmatrix} F_1 & PW_1 & PRI_1 \\ F_2 & PW_2 & PRI_2 \\ \vdots & \vdots & \vdots \\ F_m & PW_m & PRI_m \end{pmatrix}$$

$j =$ the emitter class index

$m =$ number of frequencies, pulse width and pulse repetition interval

Emitter class model

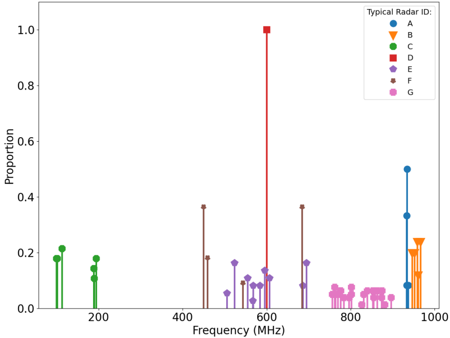
- Don't consider the temporal aspect
- Construction of a measure that describes each RADAR belonging to a reference database based on its frequencies and pulse width:

$$\mu_j = \sum_{m=1}^{M} \alpha_m \delta_{f_m, pw_m} \tag{1}$$

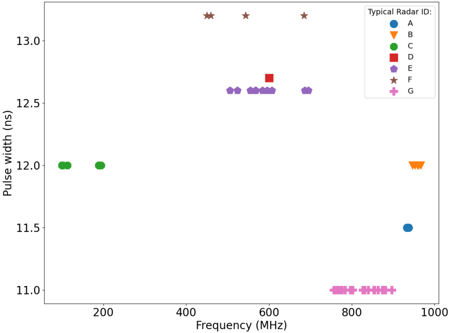
M = the number of frequencies and pulse width on which the RADAR transmits
α = the weight of the frequency and pulse width
j = the index of the transmitter in the database
δ = dirac mass (with $\sum \alpha_m = 1$)

Emitter Class example

Figure: Representation of **simulated** RADARs classes. Each color represents a simulated emitter class



(a) 1 dimension: Frequency



(b) 2 dimensions: Frequency and Pulse width

Optimal Transport Approach in 1 dimension

- Idea: Compare distributions of datasets to define a distance
- Group 0 and 1 **belong** to the same dataset
  - ✔ **Similar** distribution
  - ✔ **Low** transport cost
- Group 1 and 2 **don't belong** to the same dataset
  - ✘ **Different** distribution
  - ✘ **High** transport cost

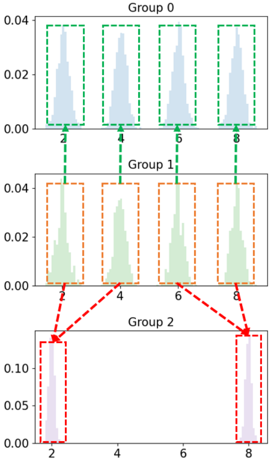


Figure: Histograms of 3 datasets.

Optimal Transport explanation

- Transporting distribution to another has a cost:

$$C(\mathbf{P}) = \sum_{n=1}^{N} \sum_{m=1}^{M} C_{nm} P_{nm} = \langle \mathbf{C}, \mathbf{P} \rangle \tag{2}$$

$C(\mathbf{P})$ = Total cost

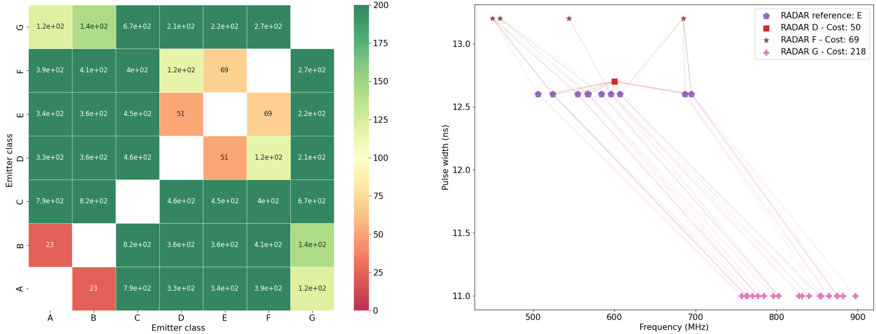
C_{nm} = cost transporting unit mass from x_n to y_m (transport cost)

P_{nm} =quantity of mass taken from x_n to y_m (transport plan)

- The optimal transport plan is a simple minimization problem:

$$\mathbf{P}^{\star} = \underset{\mathbf{P} \in \mathbf{R}_{+}^{N \times M}}{\text{argmin}} \langle \mathbf{C}, \mathbf{P} \rangle \text{ such that } \mathbf{P}\mathbf{1}_M = \mathbf{a}, \mathbf{P}^T \mathbf{1}_N = \mathbf{b}^T. \tag{3}$$

Optimal transport plan between emitters classes

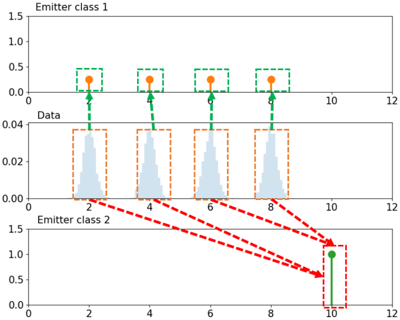


(a) Cost matrix between previous emitters classes.

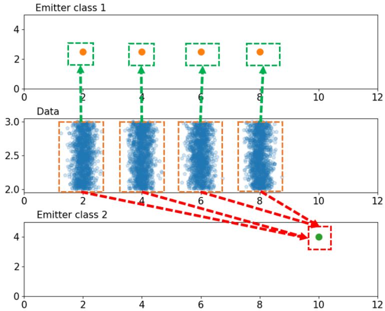
(b) Transport plan between emitter E toward emitters D, F and G.

Identification Approach

Figure: Comparison between a dataset with two **simulated** emitters classes.



(a) Frequency.



(b) Frequency and Pulse width.

Set of pulses model and Identification

- Construction of a probability distribution from the deinterlacing set of pulses based on frequency and pulse width:

$$\nu = \frac{1}{M} \sum_{m=1}^{M} \delta_{f_m, pw_m} \tag{4}$$

with M the number of pulses in the set.

- Identification of the emitter class by assigning the closest RADAR class in the optimal transport distance sense to each set of pulses:

$$j^\star = \underset{\mathbf{j} \in (1, \ldots, J)}{\operatorname{argmin}} \, d\left(\mu_j, \nu\right). \tag{5}$$

with J the number of emitters classes

Content

Classification output for set of pulses 1

- ✔ Correct identification
- ✔ **Significant** distance gap between the two first outputs

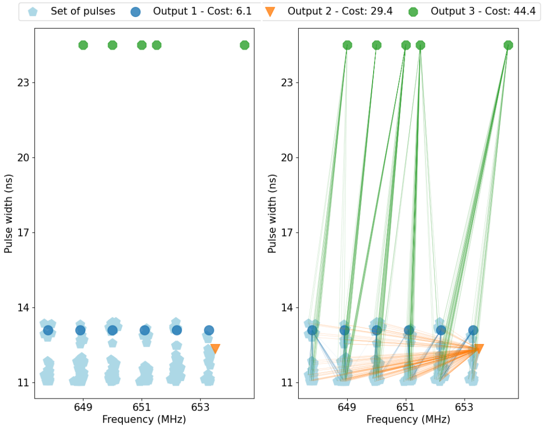


Figure: Transport plan between the pulses and the three closest emitter classes identified by the algorithm.

Classification output for set of pulses 0

- ✔ Correct identification
- ⚠ **Low** distance gap between the two first outputs
- ⚠ Large spread of the pulse width

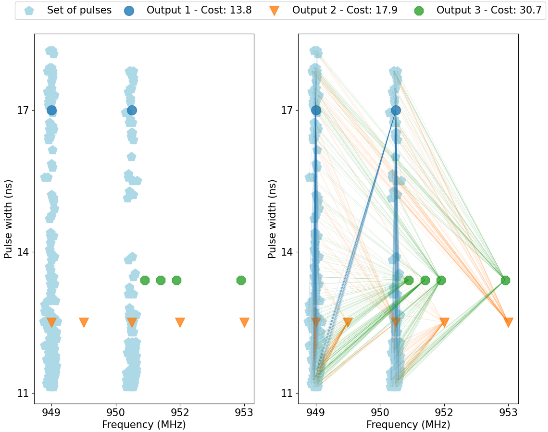


Figure: Transport plan between the pulses and the three closest emitter classes identified by the algorithm.

Another example: wrong classification

- Another example of classification performed on another signal

✘ Wrong identification

☛ Significant pulse width error

☛ Frequency and pulse width not sufficient

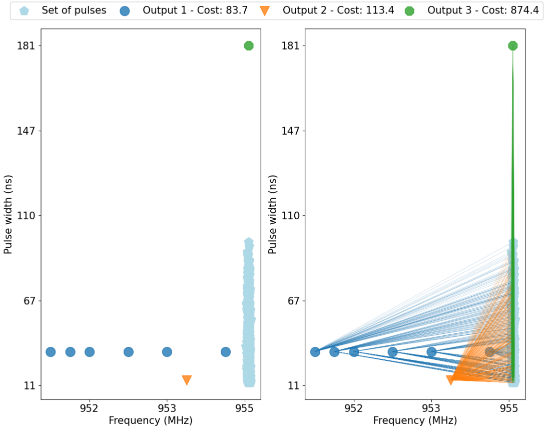


Figure: Transport plan between the pulses and the three closest emitter classes identified by the algorithm.

Globals Classification Results

Table: Empirical results of the classification made on 3608 set of pulses.

Correct classification position	Frequency	Frequency and Pulse Width
First	94.1%	95.8%
Second	5.7%	3.8%
Third	0.1%	0.1%
More	0.1%	0.3%

Content

Conclusion and Perspectives

- Works on moderately complicated cases with few data
- Methodology can handle a large number of classes to identify
- **And after?**
  - Modelisation of the pulse width spread with new distribution
  - Adding a third dimension in the optimal transport theory with the Pulse Repetition Interval

Thank you for your attention!