Low Probability of Interception Radar Signals Detection, Comparison of a YOLOv8 Model and a Conventional Signal Processing Method

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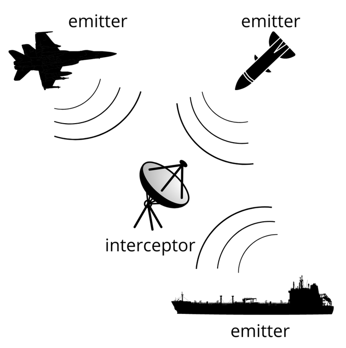
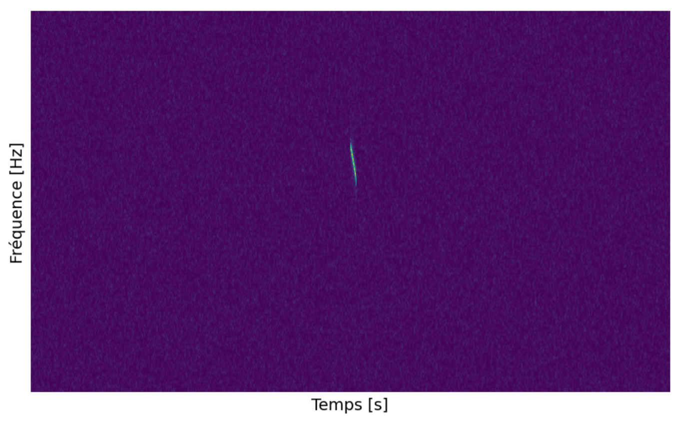
Interception of LPI Radar Signals



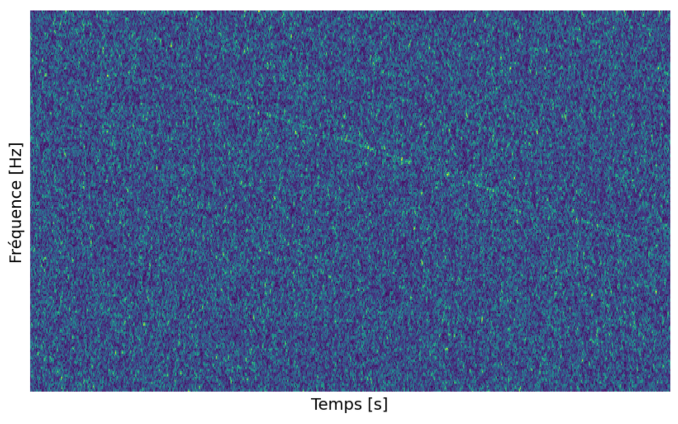
Objective: Detect an unknown signal emitted by an adversary radar

Characteristics of LPI Signals [1]:

- Wideband and long pulse
- Intrapulse modulation
- Low emitted power
- Agile waveform parameters (intrapulse and interpulse)
- Good ambiguity function properties
- Blends into complex RF environment



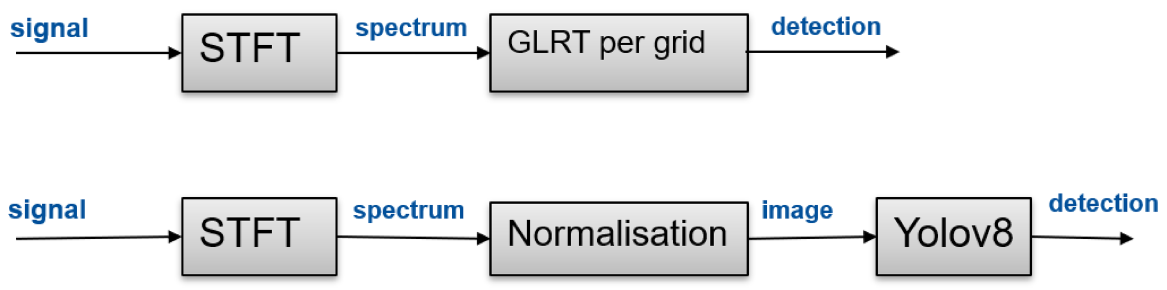
Conventional pulse



LPI pulse

How to detect an unknown signal spread in the time frequency plan ?
Conventional methods struggle to detect LPI signals ! [2]

Two evaluated methods



The grid-based Generalized Likelihood Ratio Test (GLRT) is a conventional detection method that compares the energy within the cells of the spectrum to a thershold.
The deep learning-based YOLOv8 detector, which learns to recognize LPI waveforms and generalizes its detection during inference.

Signal Models and Pre-processing

Received Signal Model:

$$s(t) = A\exp(j\Phi(t)) + n(t) \tag{1}$$

LPI Waveforms Considered [3]:

- Linear Frequency Modulation (LFM)
- Squared Frequency Modulation (SFM)
- Polyphase Codes (P1, P2, P3, P4, Frank, Barker)
- Costas Frequency Codes

Time-Frequency Representation: Short Time Fourier Transform (STFT)

$$\boldsymbol{Z}[t_i, f_j] = \sum_{k=1}^{N} s[t_k]\cdot w[t_k - t_i]\cdot e^{-i2\pi k\frac{f_j}{f_S}} \tag{2}$$

Detector using Generalized Likelihood Ratio Test (GLRT)

STFT Vector Model:

Let $\boldsymbol{z}$ be a vector composed of n STFT cells, following a circular complex normal distribution:

$$\boldsymbol{z} \sim \mathbb{C}N(\boldsymbol{m_z}, \sigma^2 \boldsymbol{I_n})$$

where $\boldsymbol{m_z}$ is the mean of the signal and $\sigma^2\boldsymbol{I_n}$ is the covariance matrix, with σ^2 being the noise variance.

GLRT Hypothesis Test:

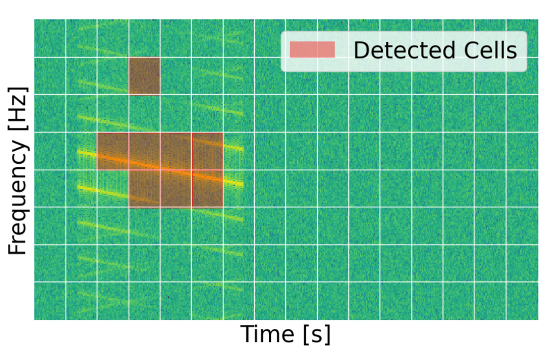
- H_0: $\boldsymbol{m_z} = \boldsymbol{0_n}$ (Noise only)
- H_1: $\boldsymbol{m_z} \neq \boldsymbol{0_n}$ (Signal + noise)

The generalized likelihood ratio test with f the density probability function is :

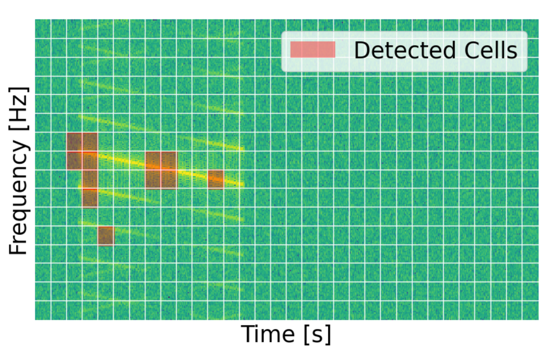
$$L(\boldsymbol{z}) = \frac{\max_{\boldsymbol{m_z}} f(\boldsymbol{z}; H_1)}{f(\boldsymbol{z}; H_0)} > \gamma \quad \iff \quad \|\boldsymbol{z}\|^2 > \gamma'_{n,P_{FA}} \tag{3}$$

Grid GLRT Algorithm

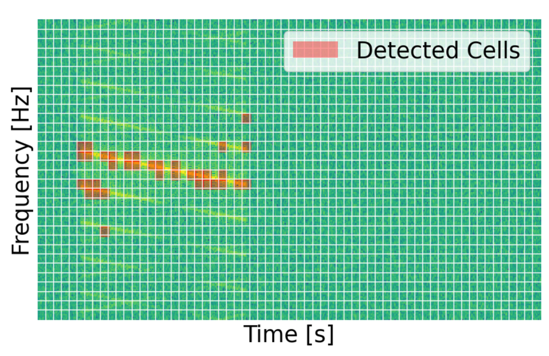
We applied the GLRT to a gridded spectrum with varying cell resolutions, aligning it with the convolutional structure of YOLOv8.



Grid with 32×32 cells

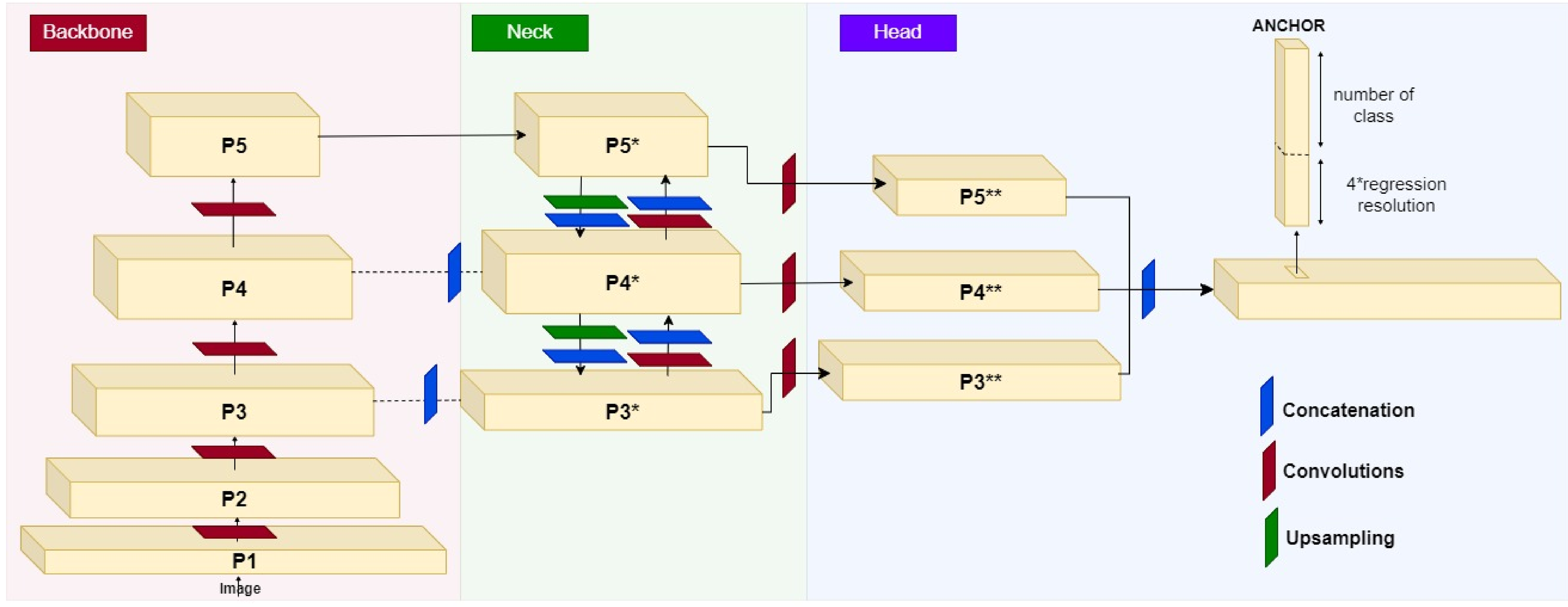


Grid with 16×16 cells



Grid with 8×8 cells

YOLOv8 Architecture



The YOLOv8 model is based on Convolutional layers extracting features from different level of resolutions and predicting both the bounding boxes and the associated class labels.

YOLOv8 Loss Function: $\mathcal{L} = \mathcal{L}_{cls} + \mathcal{L}_{box}$

- $\mathcal{L}_{cls}$: Classification loss (Focalized Cross Entropy Loss)
- $\mathcal{L}_{box}$: Bounding box regression loss (BBox Loss + Density Focalised Loss)

We used YOLOv8n, which is the smallest YOLOv8 model.

Testing and Training Dataset, only simulated data

Dataset	Total Number of Samples	Memory	PSNR Range
Training Dataset	6,000,000	4 TB	0 dB to 20 dB
Testing Dataset	40,000	27 GB	-10 dB to 30 dB

Different dimensions was used to simulate the signals in the testing dataset

Metrics: Peak Signal-to-Noise Ratio, False Alarm and True Detection

The **PSNR** is used to measure the ratio between the maximum signal power and the average noise power in time-frequency images.

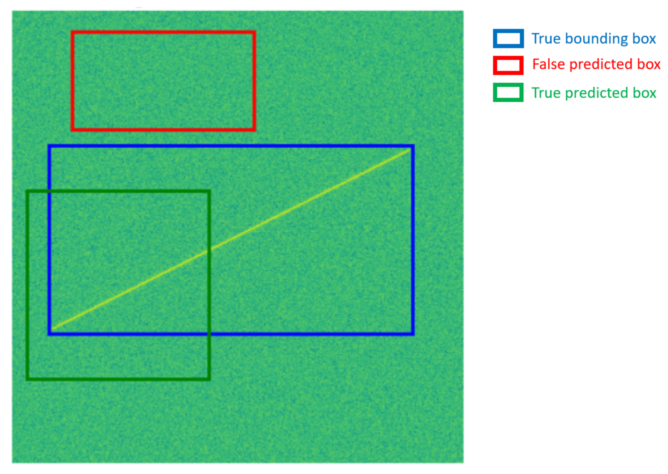
$$\text{PSNR} = 10\log_{10}\left(\frac{\max_{t,f}\|\mathbf{Z_s}(t,f)\|^2}{\frac{1}{T_w B_w}\sum_{t,f}\|\mathbf{Z_b}(t,f)\|^2}\right) \tag{4}$$

where $\mathbf{Z_s}$ is the noiseless signal spectrogram and $\mathbf{Z_b}$ is the noise spectrogram.

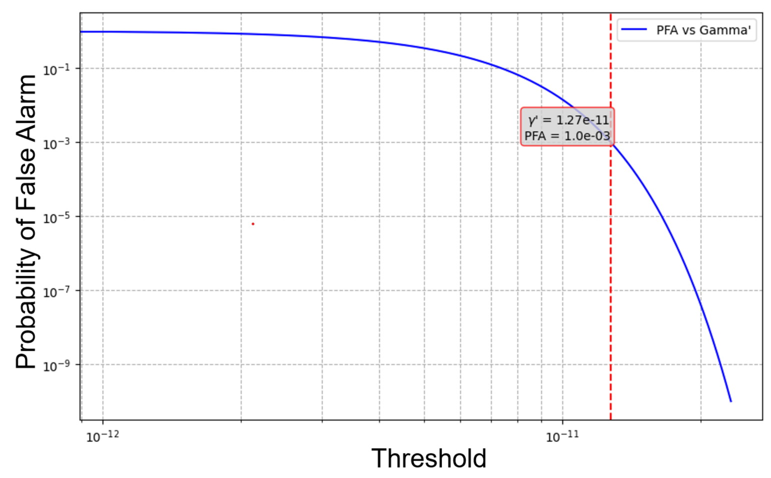
Bounding Box :

A bounding box is defined by the coordinates of its center, along with its width and height.

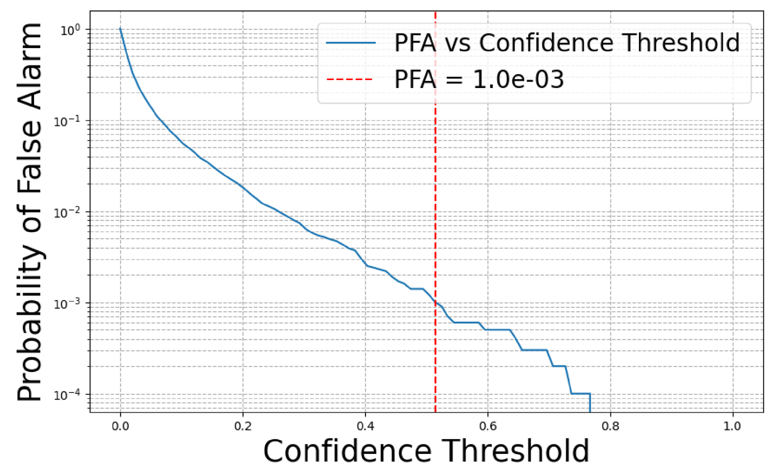
False Alarm (FA) and True Detection are estimated by examining the intersection between the predicted and true bounding boxes.



False Alarm



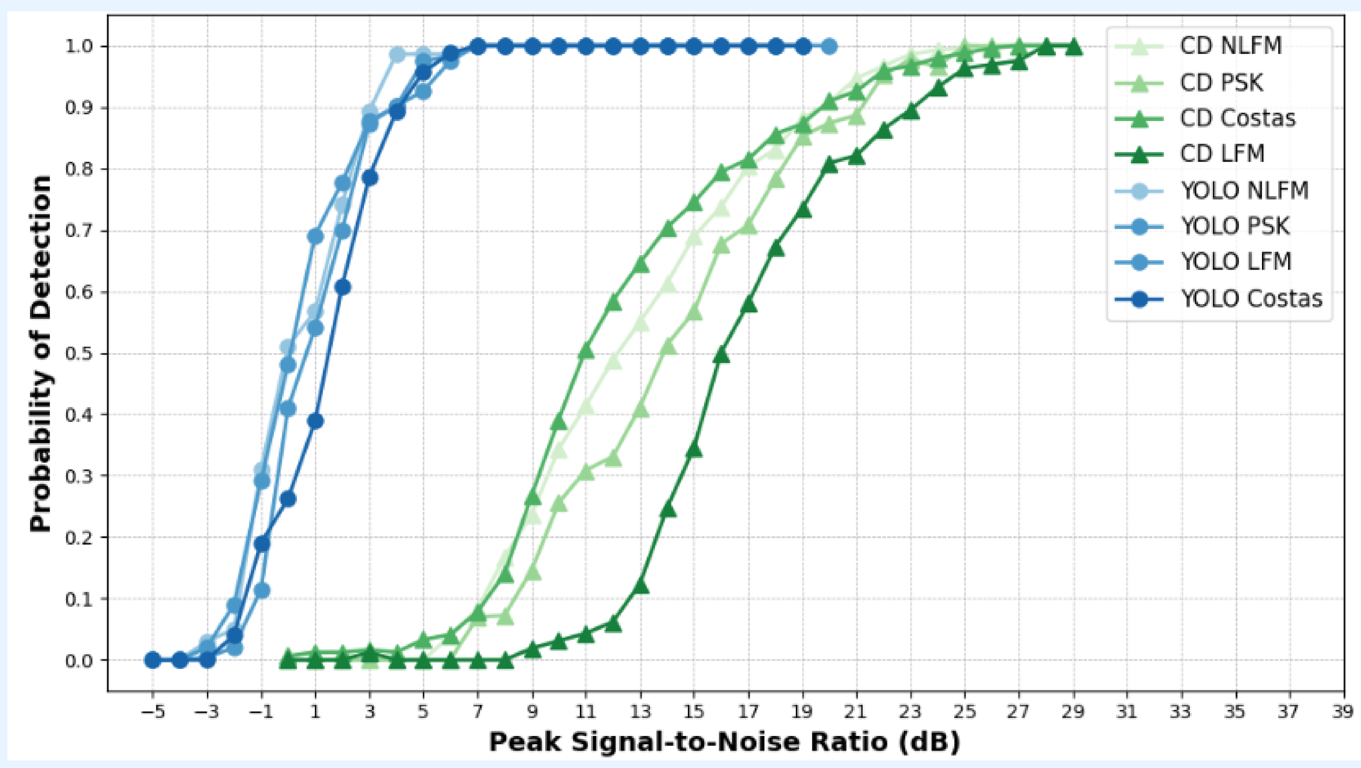
Theorical False Alarm for Grid GLRT detector of 8×8 cells.



Emprical False Alarm for Yolov8 detector.

For each grid in the Grid GLRT algorithm, the threshold was set based on the theoretical FA. For the YOLOv8 detector, the confidence score was used empirically to threshold the FA.

Results: Detection Performance Comparison



Probability of detection comparison between YOLOv8 (blue) and conventional detector (CD) (green). A gain of 5dB in PSNR for the Yolov8 detector.

Conclusion and References

- A **YOLOv8 algorithm** has been trained and tested for detecting LPI signals in time-frequency images.
- Performances have been compared to a **conventional GLRT per grid detector** under the same PFA.
- The **YOLOv8 detector** achieves an **average gain of 5 dB** with low dispersion between waveforms.
- All waveforms are detected with **nearly 100% detection probability** at **6 dB of PSNR**.

[1] P. Pace, Detecting and Classifying Low Probability of Intercept Radar, Second Edition, Artech, 2008.

[2] P. Camuso, & all, "A comprehensive analysis on detection performances of LPI signals filtering strategies," EuRAD, 2009, pp. 125-128.

[3] G. Schrick all, "Interception of LPI radar signals," IEEE International Conference on Radar, Arlington, USA, 1990, pp. 108-111.