Machine-learning-based spectrum sensing enhancement for software-defined radio applications

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Who we are

- Capgemini engineering: 270,000 experts worldwide A strong international presence in nearly 50 countries
- 8 research programs in France:
  - Future of mobility
  - Future of energy
  - Future of healthcare
  - Applied AI
  - Future of industry
  - Future of engineering
  - Future of networks & compute
  - Future of People@Work
Our activities

• Aeronautical Cognitive Transceiver (ACT) is a project attached to Future of networks & compute program.
• The ACT project aims to find the best digital radio architectures for optimal use of frequency bands.
  • 2 R&D lead engineers:

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Main concepts:

- **Software-Defined Radio (SDR):**
  Complex analog system design has been replaced by simpler software and signal processing algorithms. SDR propose: lightweight, compact, multipurpose & flexible wireless systems.

- **Cognitive Radio (CR):**
  Thanks to the flexibility of SDR systems, CR technology enables intelligent wireless communication systems. CR is capable of:
  - monitoring its environment
  - analyzing what it senses
  - deciding on the information obtained
  - adapting the system to its environment

- **Spectrum Sensing (SS)**
  The CR purpose in our case is to manage the frequency spectrum. The first step is to sense the available spectrum.
Machine Learning algorithms:

Data Source → Channel encoder → Modulation → TX front-end

Amplitude shift keying

Data Sink → Spectrum Sensing → Demodulation → Filter → RX front-end

Machine learning:
- Random Forest (RF)
- Naïve Bayes (NB)
- Gradient Boosting Machine (GBM)
- Support Vector Machine (SVM)

Propagation channel → AWGN
How to model a system with SS?

• An environment with several primary users (PU) is considered,
• Only one secondary user (SU) is in this environment,
• The PUs randomly walk in the environment,
• The SU observes the environment to detect the absence of a PU to occupy the available spectrum,
• The SU must not disturb the PUs.
• Two hypotheses should be considered in this case:

\[ H_0: x[n] = w[n] \quad \text{PU not detected} \]
\[ H_1: x[n] = s[n] + w[n] \quad \text{PU detected} \]

PU signal

additive white Gaussian noise (AWGN) with the distribution \( N(0,\sigma^2) \).
How to evaluate the system performance?

Two model system hypotheses lead us to 4 different possibilities:

- We could not detect any signal because it is not there!  
  **True Negative (TN)**

- We could not detect any signal, however it is there!  
  **False Negative (FN)**

- We detect a signal because there is a signal here!  
  **True Positive (TP)**

- We detect a signal but there is a problem!  
  **False Positive (FP)**

Evaluation metric for binary classification problems:

- Receiver Operating Characteristic (ROC) curve: TP vs FP
- Area under ROC curve (AUC)
Proposed framework:

- Use the entire transmission chain to train the ML algorithms,
- The ML algorithms are trained to sense the available spectrum,
- Use the trained ML algorithms for new data test,
- The proposed system is able to remove the channel effect.
Simulation results:

- Classic criterion: Neyman-Pearson detector

- ML algorithms

![ROC Curve for SNR = -10](image)

Without filtering

With filtering

Machine-learning-based spectrum sensing enhancement
Simulation results:

AUC for simulation results:

<table>
<thead>
<tr>
<th>Machine learning algorithm</th>
<th>Before filtering</th>
<th>After filtering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR (dB)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-20</td>
<td>-10</td>
</tr>
<tr>
<td>Random forest classifier</td>
<td>0.48</td>
<td>0.51</td>
</tr>
<tr>
<td>Naïve Bayes</td>
<td>0.49</td>
<td>0.56</td>
</tr>
<tr>
<td>Support vector machine</td>
<td>0.50</td>
<td>0.64</td>
</tr>
<tr>
<td>Gradient boosting machine</td>
<td>0.49</td>
<td>0.51</td>
</tr>
</tbody>
</table>

0.5 → no discrimination
0.7 to 0.8 → acceptable
0.8 to 0.9 → excellent
more than 0.9 → outstanding
Practical results:

ROC curve:

Area under ROC curve:

<table>
<thead>
<tr>
<th>Machine-learning-based spectrum sensing enhancement</th>
<th>Random forest classifier</th>
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<tr>
<td></td>
<td>0.64</td>
<td>0.74</td>
<td>0.51</td>
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Conclusions / Perspectives

• From the simulation results: all the algorithms have a better performance than the Neyman-Pearson classic detection method.

• The ML algorithms are able to consider the filter and channel effects in spectrum sensing.

• Naïve Bayes and SVM obtained more accurate results than GBM and random forest.

• In practice naïve Bayes is identified as the most suitable algorithm between the four studied ML algorithms.

• More complicated system combinations should be evaluated by the ML algorithms.

• More precise results can be obtained by expanding the scope of research to the cooperative signal detection.
Thanks for your attention!