Automatic Modulation Classification in Practice

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Motivation

- Numerous publications: No practical implementation in open literature
- Importance in defence applications
- Cryptanalysis can be done only after demodulation and error correction
- Modulation classification scenarios
  - Nearly all parameters of the single signal is known
  - No parameters are known in advance
Decision Theoretic Approach

- Classifiers presented in literature assume that signal parameters are known.

- Maximum Likelihood Classifier
  - Signal classified from likelihood ratios from the matched filter output.
  - The most likely candidate is given by the modulation scheme which provides the maximum value for the likelihood ratio.

- Practical implementations suffer from computational complexity.
Feature Based Detection

- Amplitude, phase and frequency features are used

- Examples
  - FM and AM: Can be distinguished by analysing amplitude

- Suboptimal but easily implementable

- Signal Characteristics
  - Analog: Sample Based, e.g. FM, AM
  - Digital: Symbol Based, e.g. MPSK, QAM

- Example Signal Features

<table>
<thead>
<tr>
<th>Modulation Scheme</th>
<th>Amplitude</th>
<th>Phase</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>FM</td>
<td>Constant</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>AM</td>
<td>Variable</td>
<td>Continuous</td>
<td>Continuous</td>
</tr>
<tr>
<td>FSK</td>
<td>Constant</td>
<td>Continuous</td>
<td>Discrete</td>
</tr>
<tr>
<td>QAM, MPSK</td>
<td>-</td>
<td>Discrete</td>
<td>-</td>
</tr>
</tbody>
</table>
Why these algorithms fail?

- Not robust in the presence of frequency or phase offsets
- Assumptions made do not hold in practical scenarios.
- Constellation Demo
Problem Statement

- Implementation of a practical realtime AMC tool
- Practical algorithms to classify
  - \{OFDM, AM, DSB, SSB, FM, ASK, PAM, PSK (MPSK), QAM, FSK (MFSK), or CPM\}
- Assumptions
  - No prior knowledge of carrier frequency, symbol rate, pulse shaping function, frequency deviation, symbol constellation or modulation index
  - For CPM, modulation index is assumed to be an integer or 0.5× integer
OFDM Classification

- Structure of OFDM signalling

- For a received signal \( y[n] \)

\[
E[y[n]y^*[n + \Delta]] = \begin{cases} 
\sigma_s^2 + \sigma_n^2 & \Delta = 0, \\
\sigma_s^2 e^{j2\pi\xi\Delta N_D} & \Delta = N_D, \\
0 & \text{otherwise.}
\end{cases}
\]
\textbf{\textit{N}_D \textit{Estimation}}

\begin{itemize}
  \item Received signal assumed to have \( D \) samples
  \item Discrete correlation represented as
  \[
  R_y(\Delta) = \frac{1}{D-\Delta} \sum_{n=1}^{D-\Delta} y[n]y^*[n + \Delta]
  \]
  \item With proper averaging
  \[
  R_y(\Delta) = \begin{cases}
    \sigma_s^2 + \sigma_n^2, & \Delta = 0, \\
    \frac{N_G}{N_D+N_G} \sigma_s^2 e^{j2\pi\xi\Delta tN_D}, & \Delta = N_D, \\
    0, & \text{otherwise}.
  \end{cases}
  \]
  \item \( N_D \) estimation formulated as
  \[
  \hat{N}_D = \arg \max_{\Delta} \{|R_y(\Delta)|\}
  \]
\end{itemize}
Discrete correlation of a received OFDM signal with data length 512.
Cyclic Prefix Length ($N_G$) Estimation

- CP length chosen as a multiple of symbol duration $N_D$
- Less correlation value for $N_G$
- High correlation value for $N_G$
The likelihood function evaluated at the estimated values is given by

$$\gamma = \tilde{\lambda}(y; N_D, N_G, \theta) |_{\hat{N}_D, \hat{N}_G, \hat{\theta}} = \tilde{\lambda}(y; \hat{N}_D, \hat{N}_G, \hat{\theta})$$

$$\gamma = \begin{cases} \frac{D}{\hat{N}_D + N_G} \hat{N}_G \sigma_s^2 & H_1, \\ 0 & H_0. \end{cases}$$

For 0dB SNR the value of threshold

$$\zeta = \frac{\sigma_s^2 + \sigma_n^2}{2} \left[ \frac{D}{\hat{N}_D + N_G} \right] \hat{N}_G$$

Reference: Tevfik Yucek and Huseyin Arslan “OFDM signal identification and transmission parameter estimation for cognitive radio applications”, *IEEE GLOBECOM 2007 proceedings*
Cyclic Moments

Definition
For a discrete time input $y(n)$ the \textit{time-varying $k$th order moment} is defined as

$$m_{ky}(n; \tau) \triangleq E\{y(n)y(n + \tau_1) \ldots y(n + \tau_{k-1})\}$$

Definition
The process $y(n)$ is said to be \textit{$k$th order cyclo-stationary} if $m_{ky}(n; \tau)$ is periodic and has a Fourier Series expansion.
Joint Classification of Analog and Digital modulation

- Used moments for classification

\[ M_{1y}^\alpha \triangleq \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} E[y(n)] e^{-j2\pi \alpha n} \]

\[ M_{2,0y}^\alpha \triangleq \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} E[y^2(n)] e^{-j2\pi \alpha n} \]

\[ M_{2,1y}^\alpha \triangleq \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} E[y(n)y^*(n)] e^{-j2\pi \alpha n} \]
## Modulation schemes and cyclic frequencies

<table>
<thead>
<tr>
<th></th>
<th>$M_{1y}^{x}$</th>
<th>$M_{2,0y}^{x}$</th>
<th>$M_{2,1y}^{x}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AM</strong></td>
<td>$f_c$</td>
<td>$2f_c$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>DSB</strong></td>
<td>N/A</td>
<td>$2f_c$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>LSB</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>USB</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>NBFM</strong></td>
<td>$f_{**}$</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>WBFM</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>MASK</strong></td>
<td>$f_c + n \times R_s$</td>
<td>$2f_c + n \times R_s$</td>
<td>$n \times R_s; n \neq 0$</td>
</tr>
<tr>
<td><strong>MPAM, PSK2</strong></td>
<td>N/A</td>
<td>$2f_c + n \times R_s$</td>
<td>$n \times R_s; n \neq 0$</td>
</tr>
<tr>
<td><strong>MPSK(M≥4), QAM</strong></td>
<td>N/A</td>
<td>N/A</td>
<td>$n \times R_s; n \neq 0$</td>
</tr>
<tr>
<td><strong>MFSK</strong></td>
<td>$f_c + 0.5 \times (2m - 1 - M) \times f_d, m = 1 \ldots M$</td>
<td>$2f_c + 0.5 \times (2m - 1 - M) \times f_d, m = 1 \ldots M$</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>CPM: h = integer</strong></td>
<td>Multiple cycle frequencies</td>
<td>Multiple cycle frequencies</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>CPM: h = 0.5 \times odd</strong></td>
<td>N/A</td>
<td>Multiple cycle frequencies</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Cyclic moment estimator

- Cyclic moment $M_{ky}^\alpha(\tau)$ can be estimated by

$$\hat{M}_{ky}^\alpha(\tau) = \frac{1}{N} \sum_{n=0}^{N-1} f_{ky}(n; \tau)e^{-j2\pi\alpha n}$$

$$f_{ky}(n; \tau) \triangleq y(n)y(n + \tau_1) \ldots y(n + \tau_{k-1})$$

- Tests developed Dandawate and Giannakis in [14] can be used to detect the presence of cycles without the knowledge of input data distribution.
Tests for the presence of cyclostationarity

- Cyclic frequencies and test statistics for conjugated second order moment
Classification Flowchart

Input: {OFDM, AM, DSB, SSB, FM, ASK, PAM, PSK, QAM, FSK, or CPM}
Input: \{OFDM, AM, DSB, SSB, FM, ASK, PAM, PSK, QAM, FSK, or CPM\}

\[ \gamma > \zeta \]

Classify as OFDM

Classify in group \{ASK, PAM, PSK, QAM, FSK, CPM\}

Classify in group \{AM, DSB, SSB, FM, FSK, CPM\}
Classification Flowchart

Input: \{OFDM, AM, DSB, SSB, FM, ASK, PAM, PSK, QAM, FSK, or CPM\}

If \(\gamma > \zeta\):
- Classify as OFDM

If \(M_{21y}^{\frac{x}{y}}\) has a cycle frequency:
  - Classify in group \{ASK, PAM, PSK, QAM, FSK, CPM\}
  - \(A\)

Else:
  - No
  - Classify in group \{AM, DSB, SSB, FM, FSK, CPM\}
  - \(B\)
Classification Flowchart2

1. \( \mathbf{A} \)

2. \( \text{Number of CF of } M_{1y}^\alpha \)
   - \( \geq 2 \)
   - \( = 1 \)

   - Classify as FSK
   - Classify as ASK

3. \( \text{Number of CF of } M_{20y}^\alpha \)
   - \( = 0 \)
   - \( = 1 \)
     - \( \geq 2 \)
     - \( = 0 \)

   - Classify as CPM: \( h = 0.5 \times \text{odd} \)
   - Classify as PAM, BPSK
   - Classify as \{QAM, MPSK: \( M \geq 4 \}\)
Classification Flowchart 3

B

Classify in group
{AM, DSB, SSB, FM}

Number of
CF of $M_{1y}^\alpha$

$= 1$

$\geq 2$

Classify as
{MFSK, CPM:
$h = \text{integer}$}

Classify as CPM:
$h = 0.5 \times \text{odd}$

Is Max of
$M_{20y}^\alpha$ a CF

no

yes

Classify as
{AM, DSB}

Classify as
{LSB, USB, FM}

Classify as
{DSB}

Number of
CF of $M_{20y}^\alpha$

$= 0$

$\geq 2$

$= 0$

$= 1$
Radio in Software

- Communication modules implemented in software
- GNURadio
  - Applications written as signal flow graphs
  - Signal processing blocks written in C++ and converted to Python
  - Modular Architecture
  - GUI: GNU Radio Companion (GRC)
USRP (Universal Software Radio Peripheral)
First Step: Spectrum Sensing

- Scan the interested frequency range by tuning the receiver front-end
- Usually averaged FFT is good enough for locating a signal
- Energy detection based on Power Spectral Density (PSD)
- Welch Estimate: For close estimate of PSD
Block Schematic

USRP → Downconverter → Filter → AMC Module

GUI Frontend
AMC Module

- Resampler → Stream to vector → Decimator → OFDM Classifier
- Stream to vector → Decimator → FFT block → Averager → $M_{1y}^{α}$ Classifier
- Squaring block → Stream to vector → Decimator → FFT block → Averager → $M_{20y}^{α}$ Classifier
- Complex to magnitude squared → Stream to vector → Decimator → FFT block → Averager → $M_{21y}^{α}$ Classifier

Tool Demo
Conclusions and Challenges

- Real-time classification is achievable
  - 7000 lines of Python code
  - Good understanding of large GNURadio codebase
  - Understanding various papers to find ones suitable for implementation.

- Practical fine tuning is essential for various parameters like
  - Signal strength threshold
  - Window length parameter and threshold for cyclic frequency tests
  - Decimation factors to match processing speed of PC

- Automatic demodulation requires more parameter estimation
Future Work

- Test AMC tool on various real life wireless signals
- Implement automatic demodulation modules
- Detect packet structure of the transmitted digital modulation data
- Detect the presence of error correcting codes
References I


Tevfik Yucek and Huseyin Arslan “OFDM signal identification and transmission parameter estimation for cognitive radio applications”, *IEEE GLOBECOM 2007 proceedings*.


References II


Fred Harris, “Let’s assume the system is synchronized”, *Globalization of Mobile and Wireless Communications*, pp.311-325, 2011.

THANK YOU
ML Classifier

\[ \tilde{r}_n = r_{I,n} + jr_{Q,n} \]

- \( P_{\tilde{r}}(r_{I,n}, r_{Q,n}/m = m_i) \) can be expressed as

\[
\frac{1}{M(i)} \sum_{k=1}^{M(i)} \frac{1}{2\pi\sigma^2} e^{-\frac{-(r_{I,n} - \sqrt{E_s}\mu_{I,k})^2 - (r_{Q,n} - \sqrt{E_s}\mu_{Q,k})^2}{2\sigma^2}}
\]

- The governing PDF of a vector \( \mathbf{r} \) of length \( N \) is

\[
P_{\tilde{r}}(\mathbf{r}_I, \mathbf{r}_Q/m = m_i) = \prod_{n=1}^{N} P_{\tilde{r}}(r_{I,n}, r_{Q,n}/m = m_i)
\]

- The most likely candidate is given by

\[
\text{arg max}_{1 \leq i \leq M} P_{\tilde{r}}(\mathbf{r}_I, \mathbf{r}_Q/m = m_i)
\]
\[ \hat{N}_G, \hat{\theta} = \arg \max_{N_G, \theta} \left\{ \tilde{\Lambda}(y; \hat{N}_D, N_G, \theta) \right\} \]

\[ = \arg \max_{N_G, \theta} \left\{ \frac{D}{\hat{N}_D + N_G} \sum_{m=0}^{N_G} \sum_{p=1}^{N_G} y[m(\hat{N}_D + N_G) + p + \theta] y^*[m(\hat{N}_D + N_S) + \hat{N}_D + p + \theta] \right\} \]

**Definition**

The process \( y(n) \) is said to be \( k \)th order cyclo-stationary if

\[ m_{k y}(n; \tau) \]

is periodic and has a Fourier Series expansion

\[ m_{k y}(n; \tau) = \sum_{\alpha \in \Omega_{m,k}} M_{k y}^\alpha(\tau) e^{j2\pi \alpha n} \]

\[ M_{k y}^\alpha(\tau) \triangleq \lim_{N \to \infty} \frac{1}{N} \sum_{n=0}^{N-1} m_{k y}(n; \tau) e^{-j2\pi \alpha n} \]