Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks

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Objective
• Correctly predict the transmitted modulation scheme

Applications
• Automatic receiver reconfiguration
  - Reduce transmission overhead due to modulation coordination
• Interference Mitigation
  - Identify and respond to interferers uniquely
• Spectrum Management
  - Automate violation notification process
Classify typical satellite communication signals

- \( \Omega = \{\text{BPSK, QPSK, 8-PSK, 16-APSK, 32-APSK, 16-QAM, 64-QAM}\} \)

Evaluate performance with

- Various capture lengths
- AWGN, -5 to 20 dB
- Es/No approximation errors < 5 dB
- Phase and frequency offsets
- Nonlinear amplifier drive levels
- DVB-S2 pilots and headers

Assume

- Coarse carrier frequency estimation
- Symbol timing recovery
- Zero ISI, matched pulse shape filters
Cumulants
- Effective at differentiating modulation order
- Well documented in literature

Neural Networks
- Universal function approximator
- Showed increased accuracy over decision tree and SVM

### Cumulant Generation

\[ S = \{s[n], ..., s[n], s^*[n], ..., s^*[n]\} \]

\[
C_{pq}(S) = \sum_{\pi} (-1)^{|\pi|-1} (|\pi| - 1)! \prod_{B \in \pi} E \left[ \prod_{i \in B} S_i \right]
\]
Preprocessing
- Coarse carrier removal
- Timing recovery
- Normalization
- $y[n], z[n]$

SNR estimator
$$\{y[n]\}_{n=0}^{N-1}$$

Cumulant estimators
$$\{y[n]\}_{n=0}^{N-1} \text{ or } \{z[n]\}_{n=0}^{N-1}$$

Neural Network
$$\hat{\Omega}_i$$

$x[n] = \text{symbols of } \Omega_i$
$g[n] = \text{Gaussian noise}$
$y[n] = Ae^{j(2\pi f_0 n T + \phi)} x[n] + g[n]$
$z[n] = y[n] y^* [n - 1]$
Neural Network Architecture

Feed-Forward Multilayer Perceptron Network

Optimizer: Adaptive Moment Estimation (Adam)

Layer 0
Dense
(10,40)
tanh

Layer 1
Dense
(40,40)
tanh

Layer 2
Dense
(40,40)
tanh

Layer 3
Dense
(40,7)
softmax

\[ \frac{\hat{E}_s}{N_0} \]

\[ |\hat{C}_{20}| \]

\[ |\hat{C}_{40}| \]

\[ |\hat{C}_{41}| \]

\[ |\hat{C}_{42}| \]

\[ |\hat{C}_{60}| \]

\[ |\hat{C}_{61}| \]

\[ |\hat{C}_{62}| \]

\[ |\hat{C}_{63}| \]

\[ |\hat{C}_{80}| \]

\[ \Omega_i \]
What does the Neural Net see?

Each frame: N point sequence in IQ

Cumulants

Constant phase-offset

Frequency-offset

AWGN

Amplifier saturation

\[ y[n] \]

\[ z[n] = y[n-1]y[n] \]
Vector Length Analysis

Feature vector generated from

\[
\{y[n]\}_{n=1}^{N} \quad N = \{1k, 2.5k, 5k, 10k\}
\]

\[
\{z[n]\}_{n=1}^{N} \quad N = \{10k, 20k, 40k, 80k\}
\]

For similar classification performance, classification based on \{z[n]\} required \sim 15x more symbols.
• Frequency offset imposes upper bound on $y[n]$ sequence length
• $z[n]$ converts fixed frequency offset into fixed phase offset
• Cumulant magnitudes are not impacted by constant phase offset
Es/No Approximation Error

- Neural net requires SNR estimation
- Imperfect estimation of SNR will degrade performance
- Most sensitive to error at low Es/No
- $y[n]$ and $z[n]$ exhibit similar responses to Es/No error
- Results provide accuracy requirements for SNR estimator
• Previous results in literature did not account for nonlinear amplification
• Amplifier simulated using Saleh model using coefficients from operational TWTA
• PSK – only one ring, not impacted by amplifier
• Classification of higher order modulations experienced significant degradation at levels where a user could expect to operate
• Additional input features needed to train neural network over this dimension
DVB-S2 Pilots and Headers

- Previous research has not measured impact of pilots/headers on classifier performance
- DVB-S2 physical layer extends alphabet of received symbols, due to inclusion of headers/pilots
- Unable to classify 16 APSK using $z[n]$ at 20 dB Es/No
- Classifier performance degradation due to DVB-S2 framing was < 5% in most cases
Next Steps and Conclusions

Next Steps
- Investigate additional features
- Implement a SNR approximation algorithm
- Classify modulation types in lab
- Add timing acquisition and carrier removal
- Classify live signals

Conclusions
- Created modulation classifier using cumulants and a neural network
- Evaluated performance over
  - Capture length
  - AWGN
  - Constant frequency and phase offset
- Extended previous work in field to include analysis over
  - SNR approximation error
  - Nonlinear amplifier distortion
  - DVB-S2 physical layer effects
Classification by Modulation

Left: $y[n]$
Right: $z[n]$

16 QAM
64 QAM
Cumulant Magnitudes

Left: $y[n]$
Right: $z[n]$

16 APSK
32 APSK
2 PSK
4 PSK
8 PSK
16 QAM
64 QAM
Probability of classifying modulation type with DVB-S2 headers (H) and pilots (P)

$\frac{E_s}{N_0} = 20 \text{ dB}$

$z[n]$ signal type