Modulation Classification of Satellite Communication Signals Using Cumulants and Neural Networks

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Automatic Modulation Classification

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

- Ω = {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

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

p-q terms   q terms

$$C_{pq}(S) = \sum_{\pi} (-1)^{|\pi|-1}(|\pi| - 1)! \prod_{B \in \pi} E\left[\prod_{i \in B} S_i\right]$$

Features

- Probability Density Function
- Spectral Statistics
- Fourier-wavelet
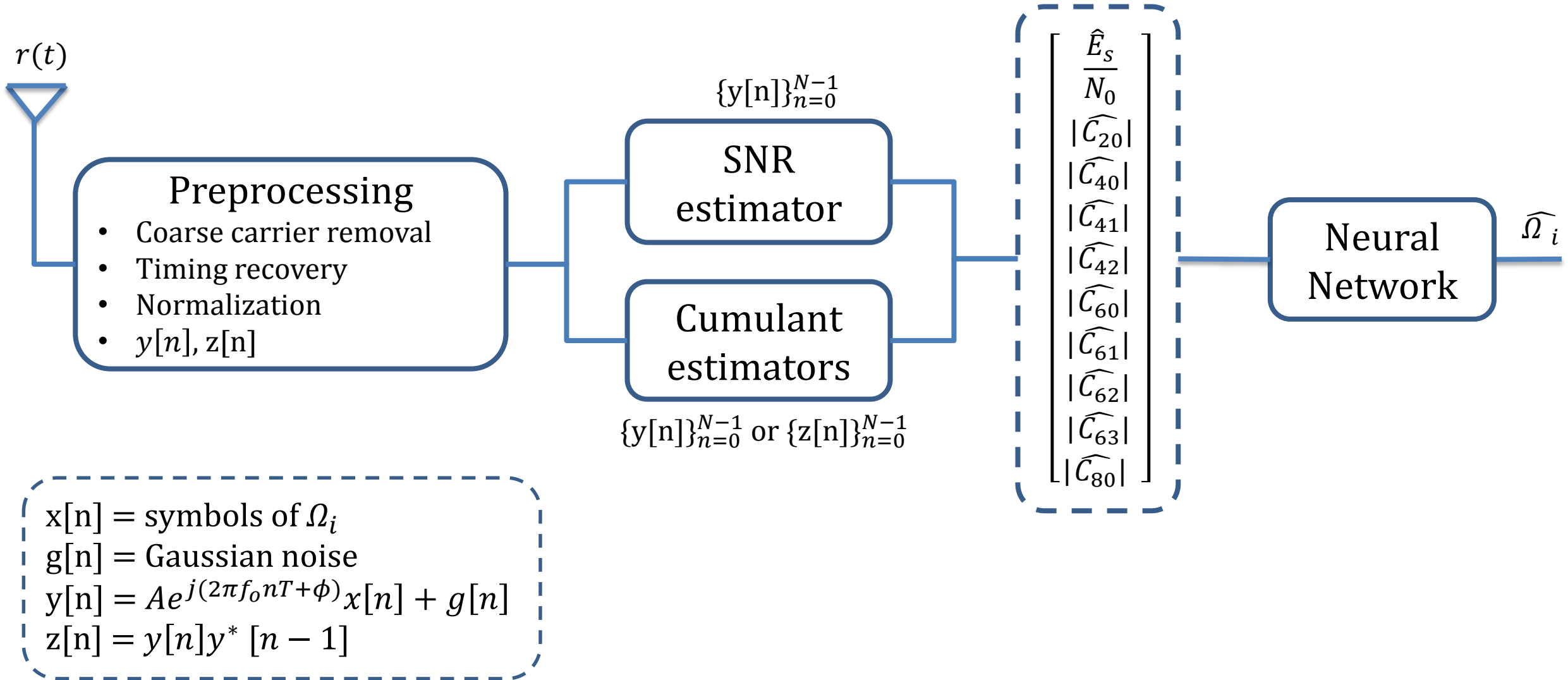- Cumulants
- Autocorrelation
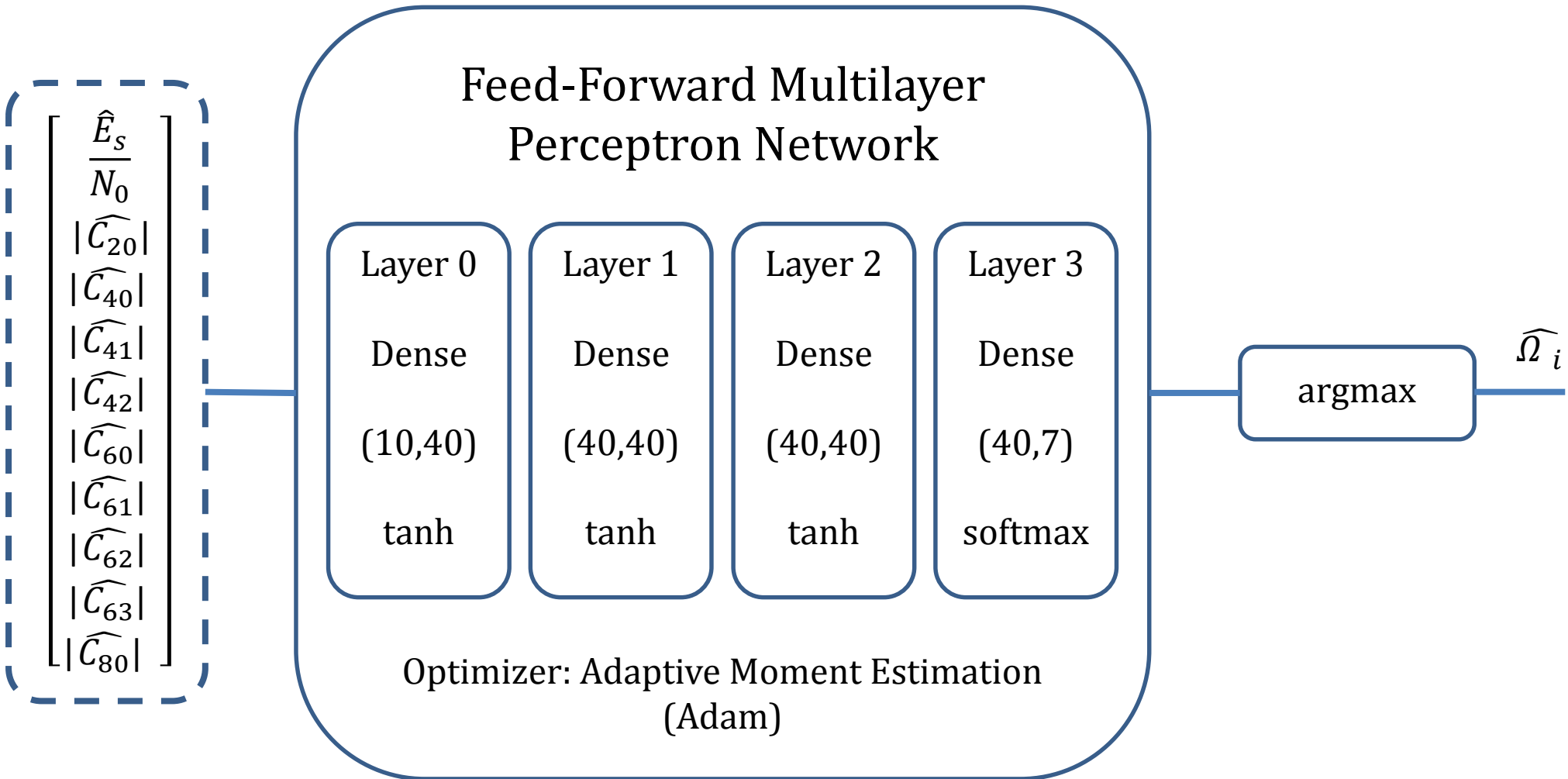- Raw IQ
- Centroids

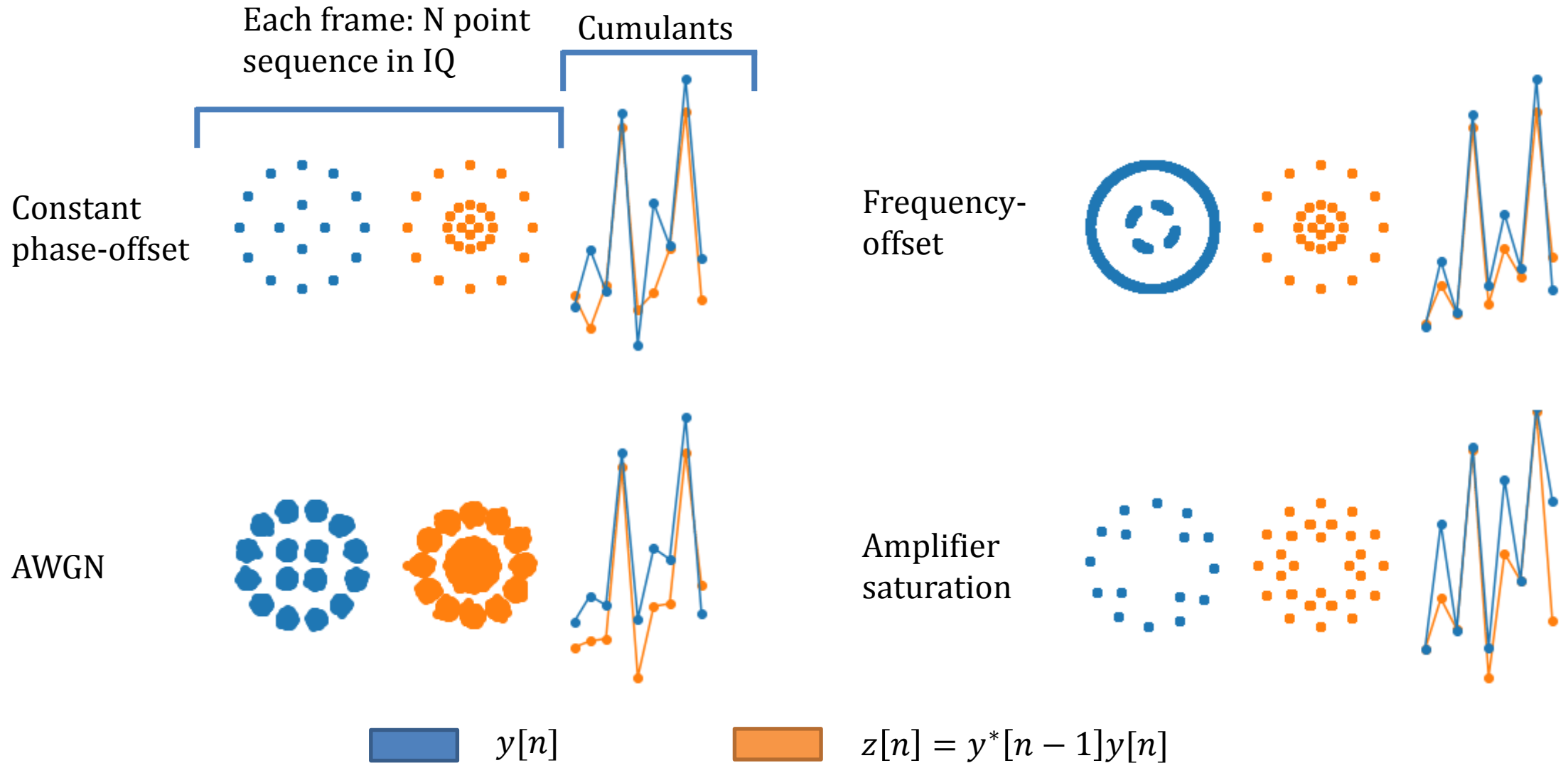### Classifiers

- Decision Tree
- Neural Network
- SVM
- Catalog Comparison
- KNN

$r(t)$

Preprocessing
- Coarse carrier removal
- Timing recovery
- Normalization
- $y[n]$, $z[n]$

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

SNR estimator

Cumulant estimators

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

$$\begin{bmatrix} \dfrac{\widehat{E}_s}{N_0} \\ |\widehat{C_{20}}| \\ |\widehat{C_{40}}| \\ |\widehat{C_{41}}| \\ |\widehat{C_{42}}| \\ |\widehat{C_{60}}| \\ |\widehat{C_{61}}| \\ |\widehat{C_{62}}| \\ |\widehat{C_{63}}| \\ |\widehat{C_{80}}| \end{bmatrix}$$

Neural Network

$\widehat{\Omega}_i$

$x[n]$ = symbols of Ω_i
$g[n]$ = Gaussian noise
$y[n] = Ae^{j(2\pi f_o nT + \phi)}x[n] + g[n]$
$z[n] = y[n]y^*[n-1]$

$$\begin{bmatrix} \dfrac{\hat{E}_s}{N_0} \\ |\widehat{C_{20}}| \\ |\widehat{C_{40}}| \\ |\widehat{C_{41}}| \\ |\widehat{C_{42}}| \\ |\widehat{C_{60}}| \\ |\widehat{C_{61}}| \\ |\widehat{C_{62}}| \\ |\widehat{C_{63}}| \\ |\widehat{C_{80}}| \end{bmatrix}$$

Feed-Forward Multilayer Perceptron Network

Layer 0	Layer 1	Layer 2	Layer 3
Dense	Dense	Dense	Dense
(10,40)	(40,40)	(40,40)	(40,7)
tanh	tanh	tanh	softmax

Optimizer: Adaptive Moment Estimation (Adam)

argmax

$\widehat{\Omega}_i$

What does the Neural Net see?

Each frame: N point sequence in IQ

Cumulants

Constant phase-offset

Frequency-offset

AWGN

Amplifier saturation

$y[n]$

$z[n] = y^*[n-1]y[n]$

Feature vector generated from

$\{y[n]\}_{n=1}^{N}$
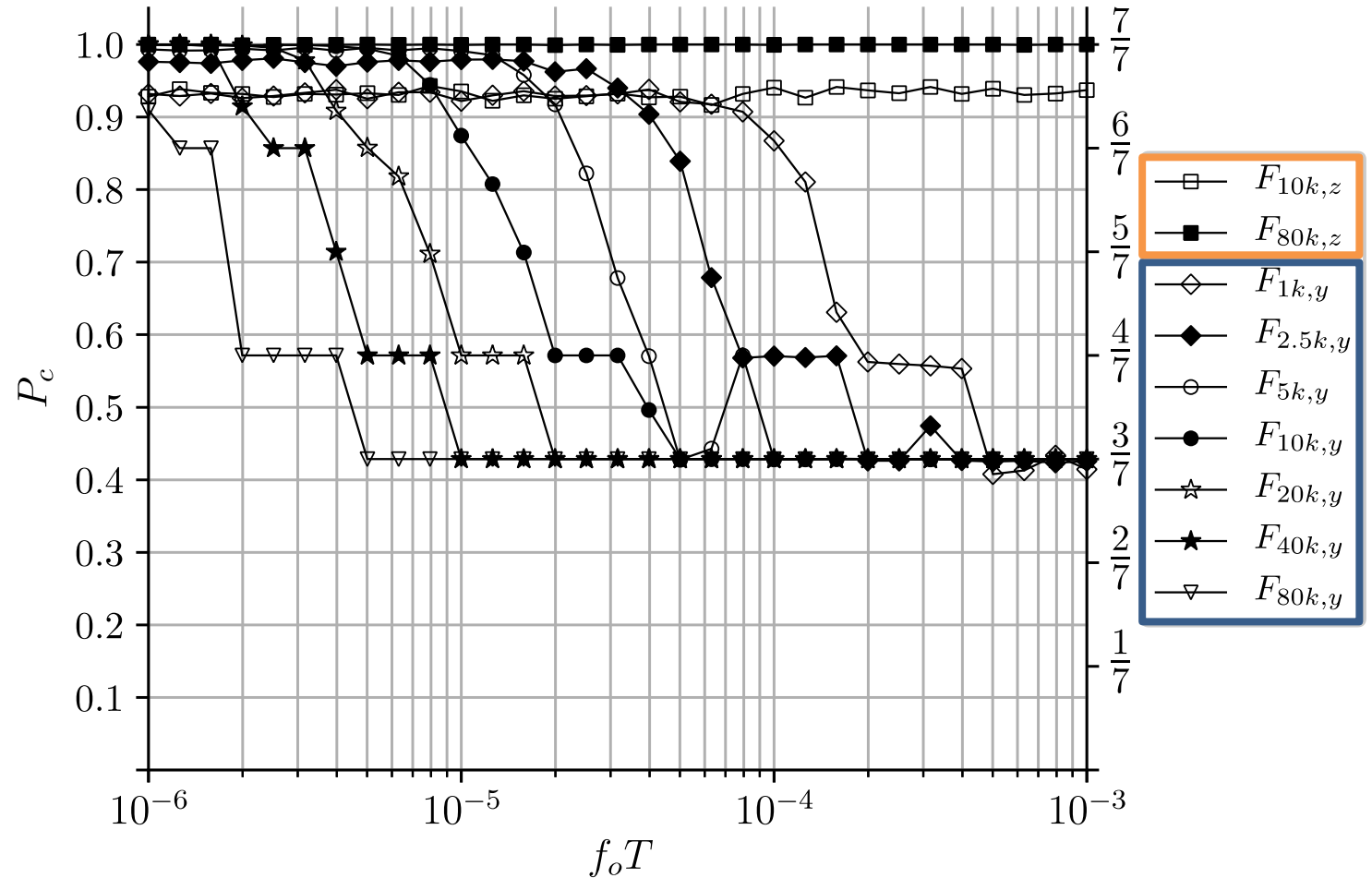$N = \{1k, 2.5k, 5k, 10k\}$
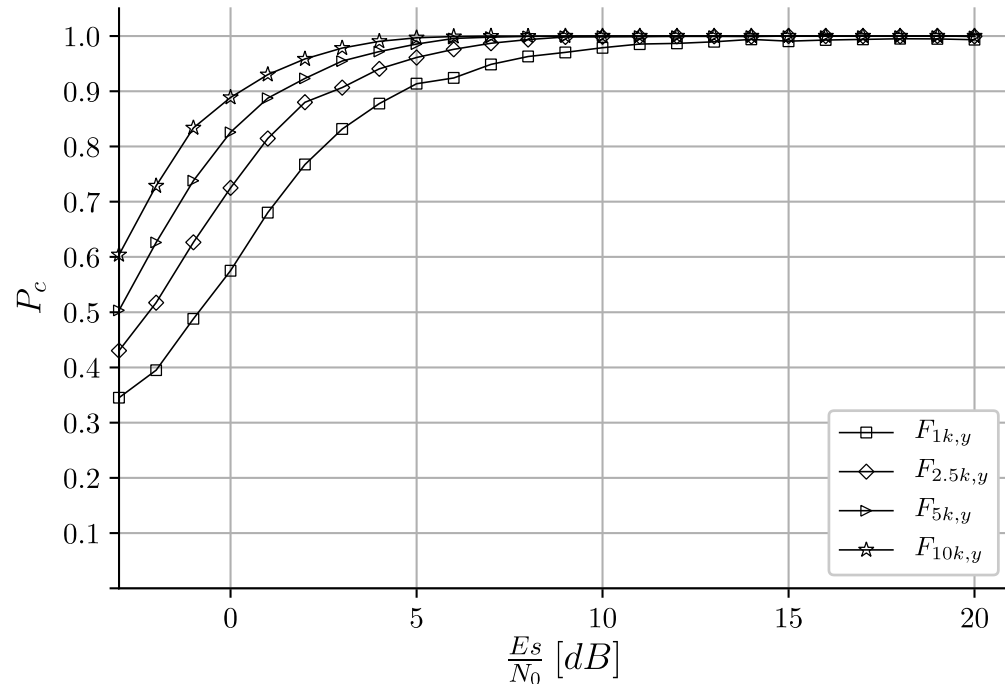
$\{z[n]\}_{n=1}^{N}$
$N = \{10k, 20k, 40k, 80k\}$
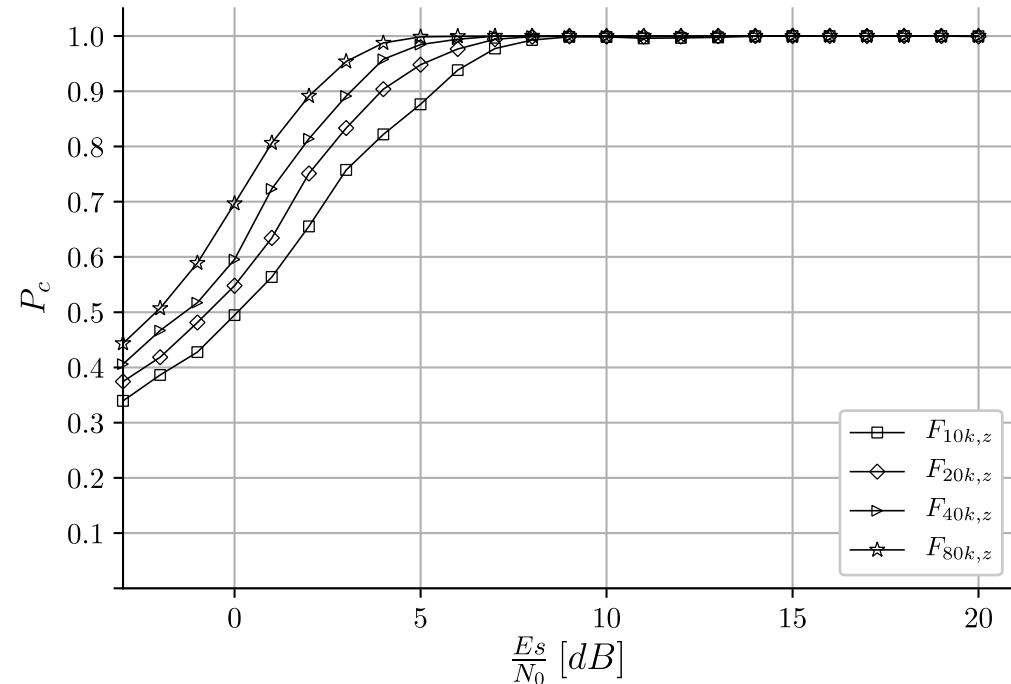
For similar classification performance, classification based on $\{z[n]\}$ required $\sim 15x$ more symbols

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- 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

- 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

Nonlinear Amplifier
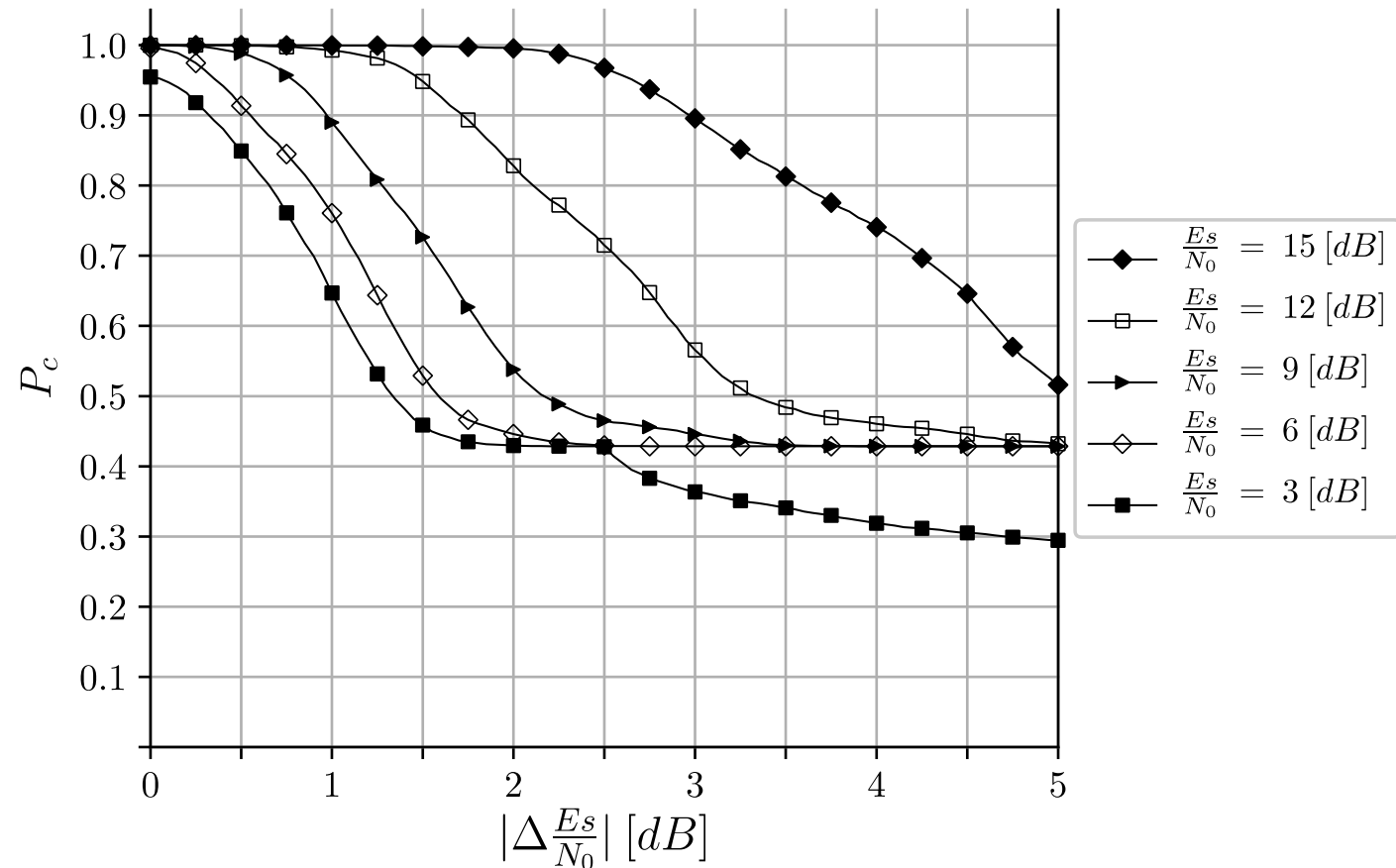
- Previous results in literature did not account for nonlinear amplification
- Amplifier simulated using Saleh model using coefficients from operational TWTA
- PSK – only one ring, not impacted by amplifier
- Classification of higher order modulations experienced significant degradation at levels where a user could expect to operate
- Additional input features needed to train neural network over this dimension

DVB-S2 Pilots and Headers
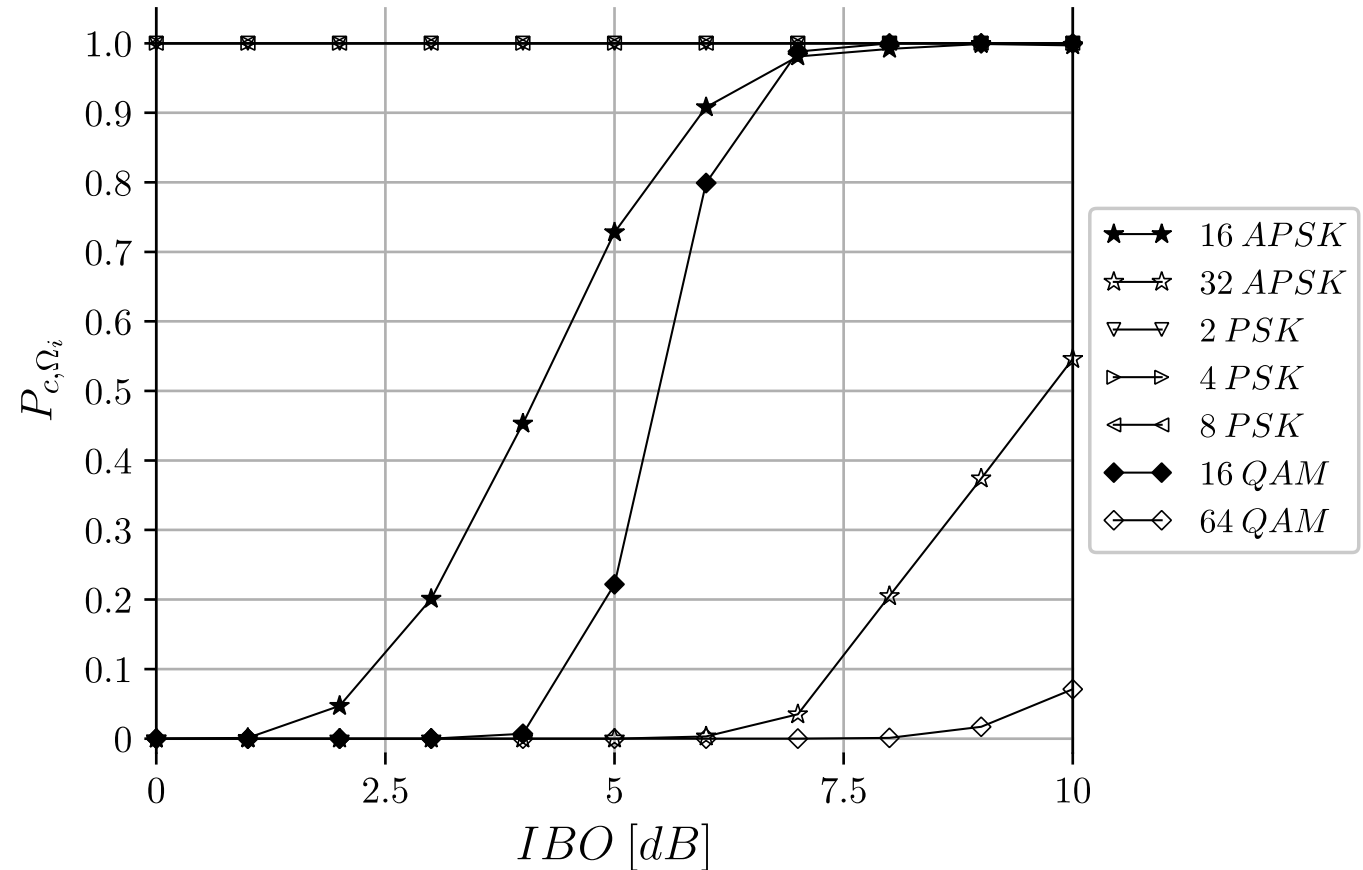
DVB-S2 Framing Structure

Header $\frac{\pi}{2}$ BPSK

Data Ω_i

Pilot QPSK

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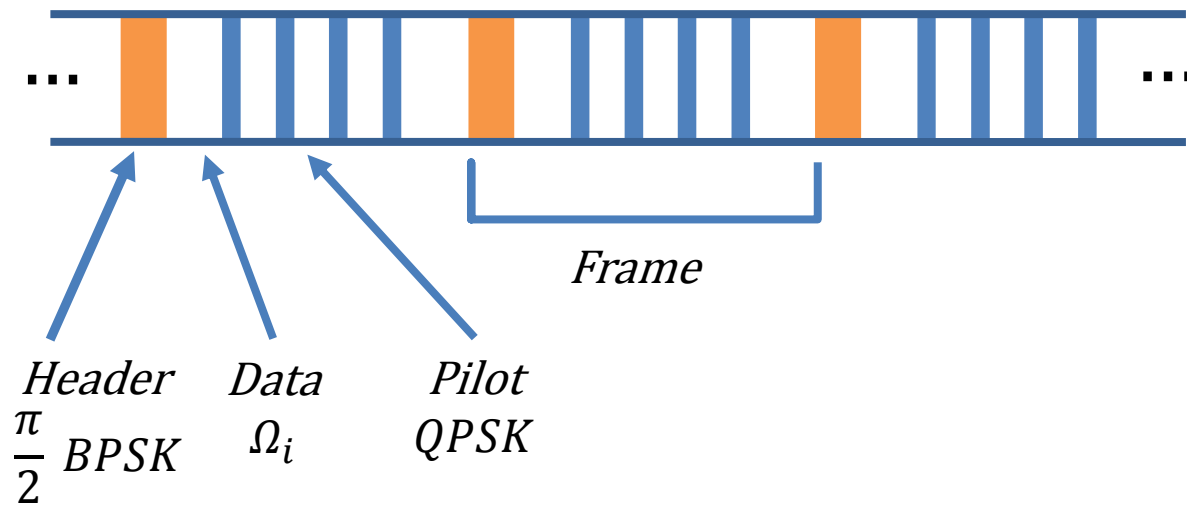
- Previous research has not measured impact of pilots/headers on classifier performance
- DVB-S2 physical layer extends alphabet of received symbols, due to inclusion of headers/pilots
- Unable to classify 16 APSK using z[n] at 20 dB Es/No
- Classifier performance degradation due to DVB-S2 framing was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

$\Omega_i = 32\ APSK$

w/o DVB-S2   w/ DVB-S2

$\{y[n]\}$

$\{z[n]\}$
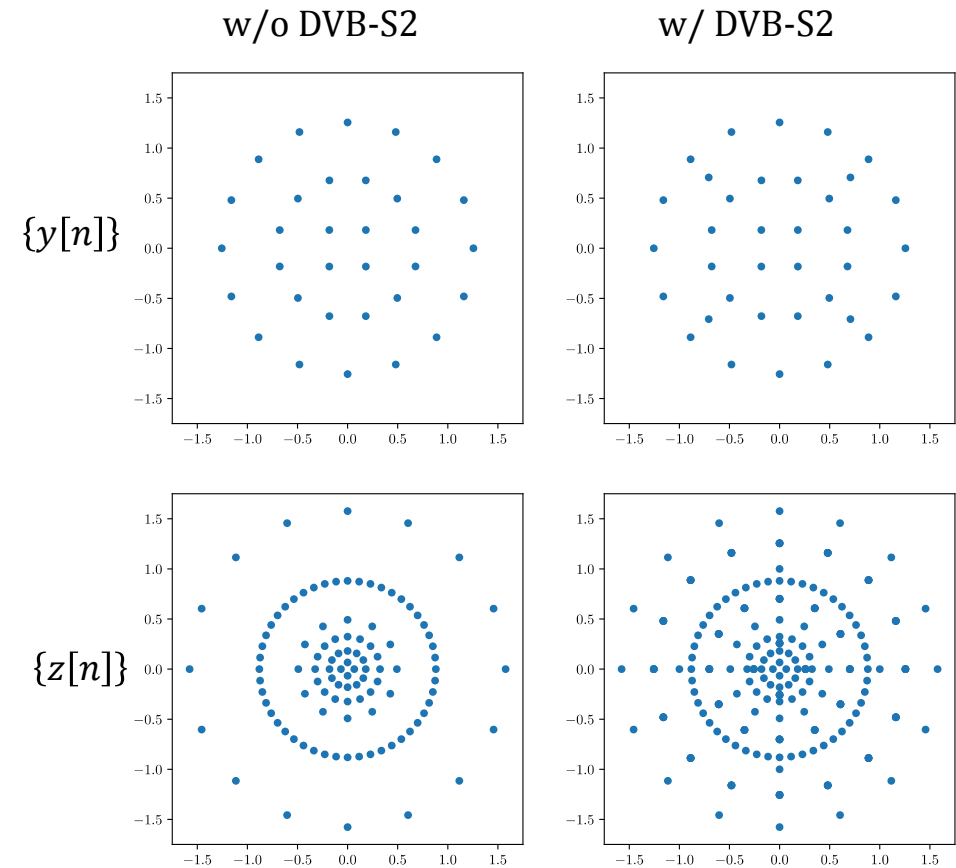
IQ constellations of 32 APSK with and without DVB-S2 physical layer

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
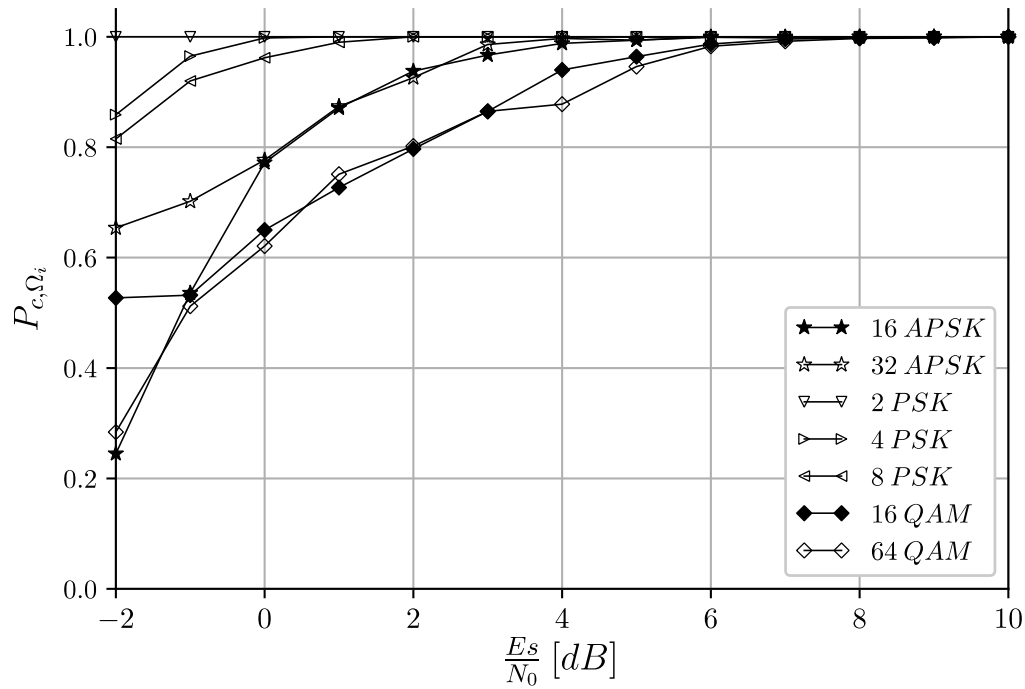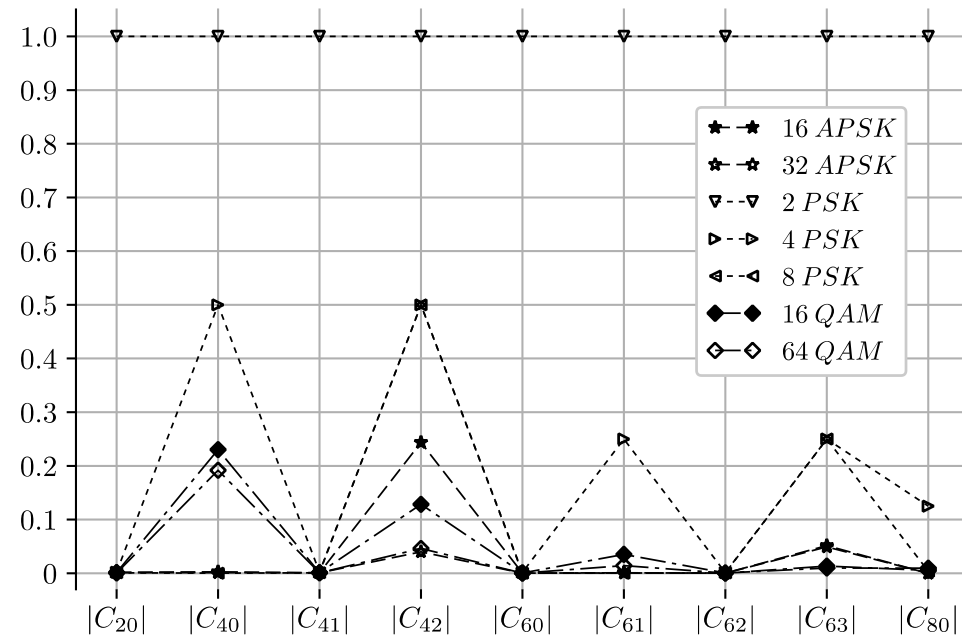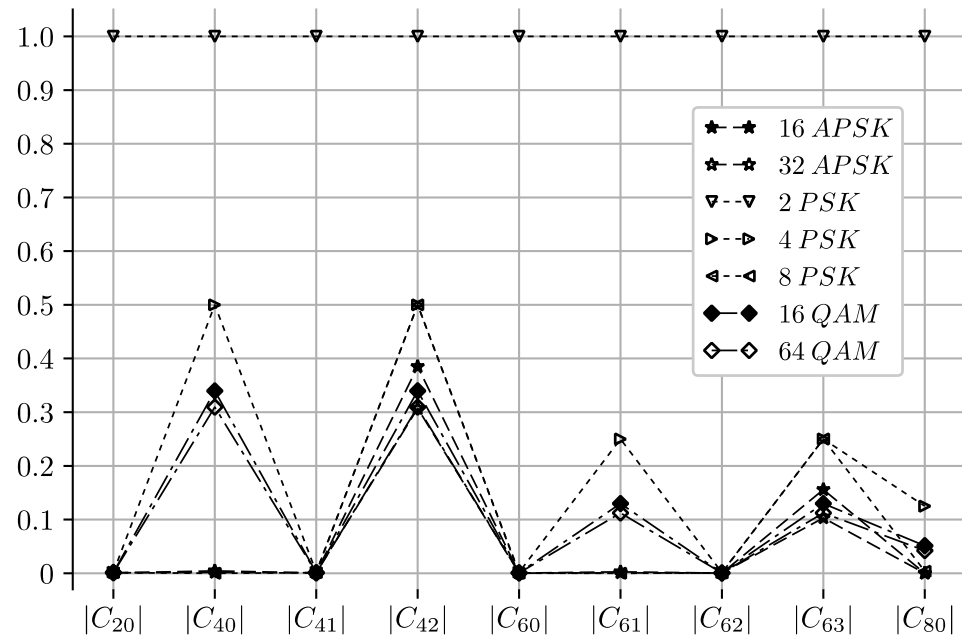 - DVB-S2 physical layer effects

Questions?

Backup Slides
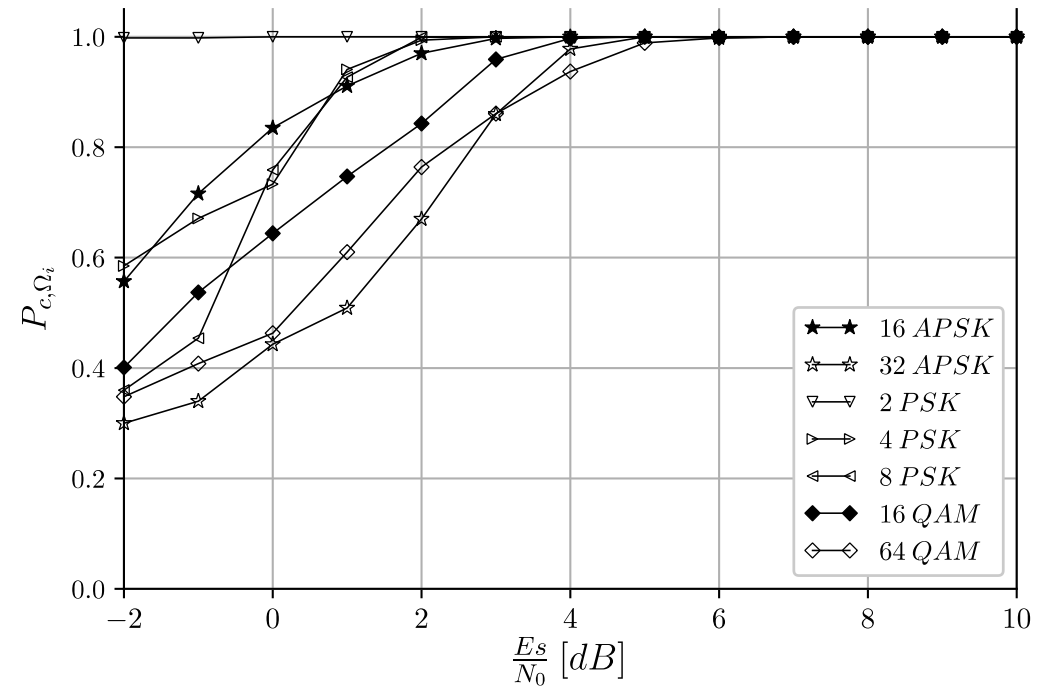
Left: y[n]
Right: z[n]

Cumulant Magnitudes

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

Probability of classifying modulation type with DVB-S2 headers (H) and pilots (P)

Es/No = 20 dB

z[n] signal type