MSG-SET-183 - DETECTION AND CHARACTERIZATION OF A UAS RF FHSS COMMUNICATION LINK

VINCENT VAN DER KNAAP, MILLAD MOURI, PETER ZWAMBORN, DANIELA DEIANA

29 April 2021

INDEX

DETECTION AND CHARACTERIZATION OF A UAS RF FHSS COMMUNICATION LINK

01. PROBLEM BACKGROUND

02. THE FHSS SIGNAL

03. DETECTION AND COARSE PARAMETER ESTIMATION

04. FINE PARAMETER ESTIMATION

05. SUMMARY

06. FUTURE WORK

TNO innovation for life

BACKGROUND
MOTIVATION AND PROBLEM DESCRIPTION

MOTIVATION

- Capabilities of Unmanned Aerial Systems (UAS), in both military and civilian applications, are growing rapidly
- UAS hardware has become ubiquitous
- Reliable detection techniques to enable appropriate counter measures is becoming crucial

PROBLEM DESCRIPTION

- Detection and characterization of a RF uplink using FHSS modulation used for drone communications

SIGNAL PROCESSING CHAIN
OVERVIEW

Received FHSS signal → Detection and Coarse Parameter Estimation → Fine Parameter Estimation

RECEIVED SIGNAL

- In this study, Frequency Hopping Spread Spectrum (FHSS) is identified as one of the main communication techniques in use by UAS.

DETECTION

- Detecting UAS through characterization of their communication link is very promising as it directly provides information useful for possible counter measures, such as smart jamming.

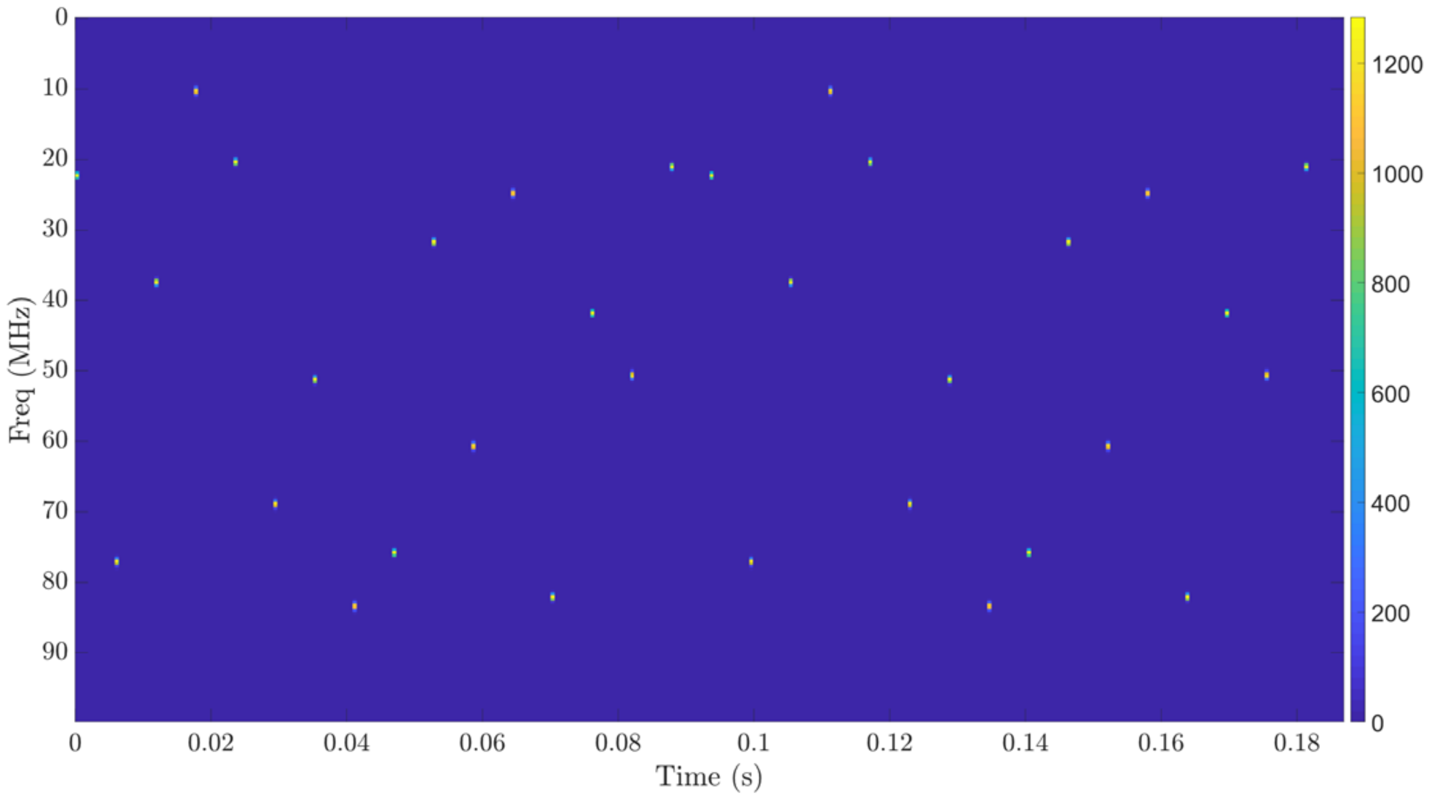
PARAMETER ESTIMATION

- An algorithm based on the combination of Wavelet Transform and Sparse Learning is investigated.

FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

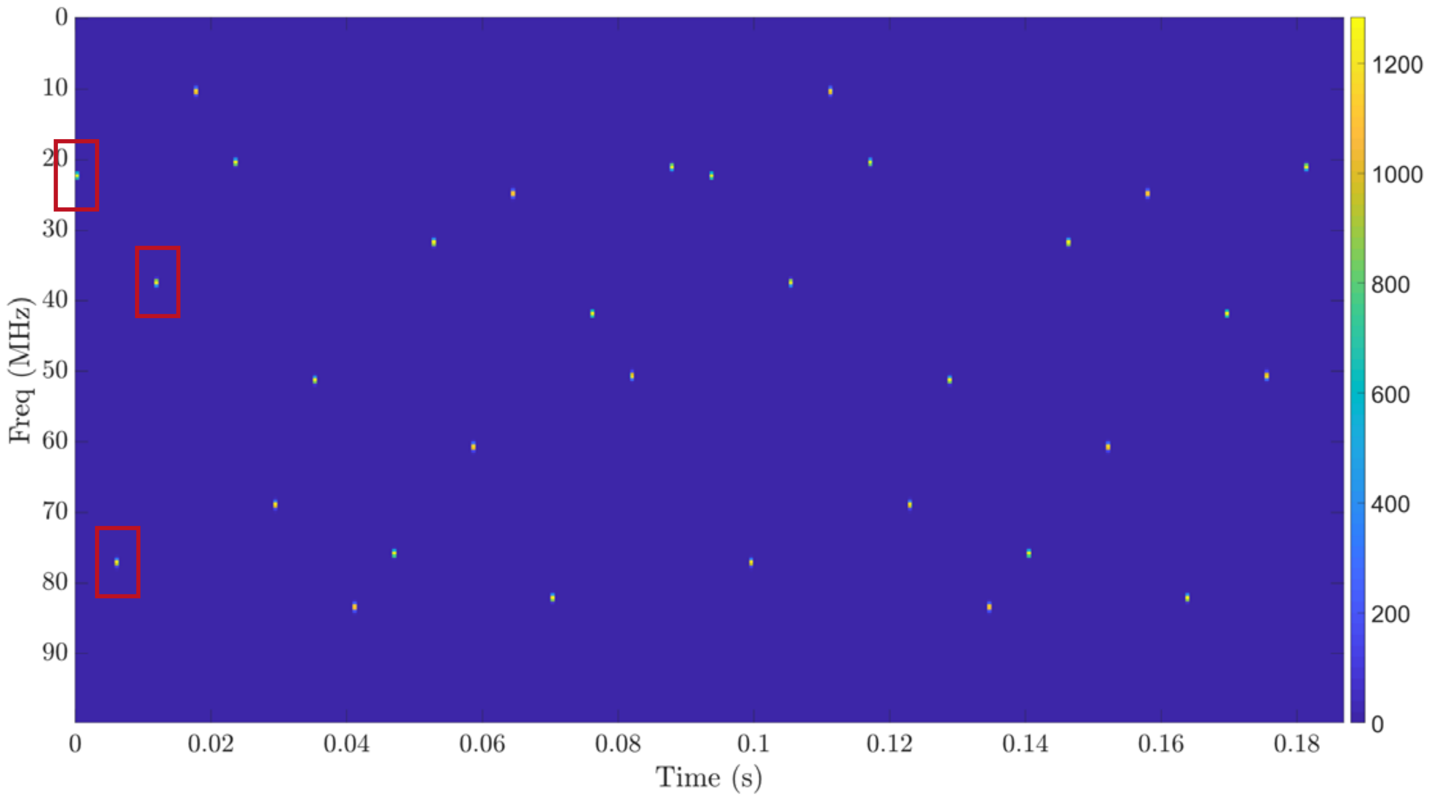
- Carrier frequency and bandwidth f_c, B;



FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

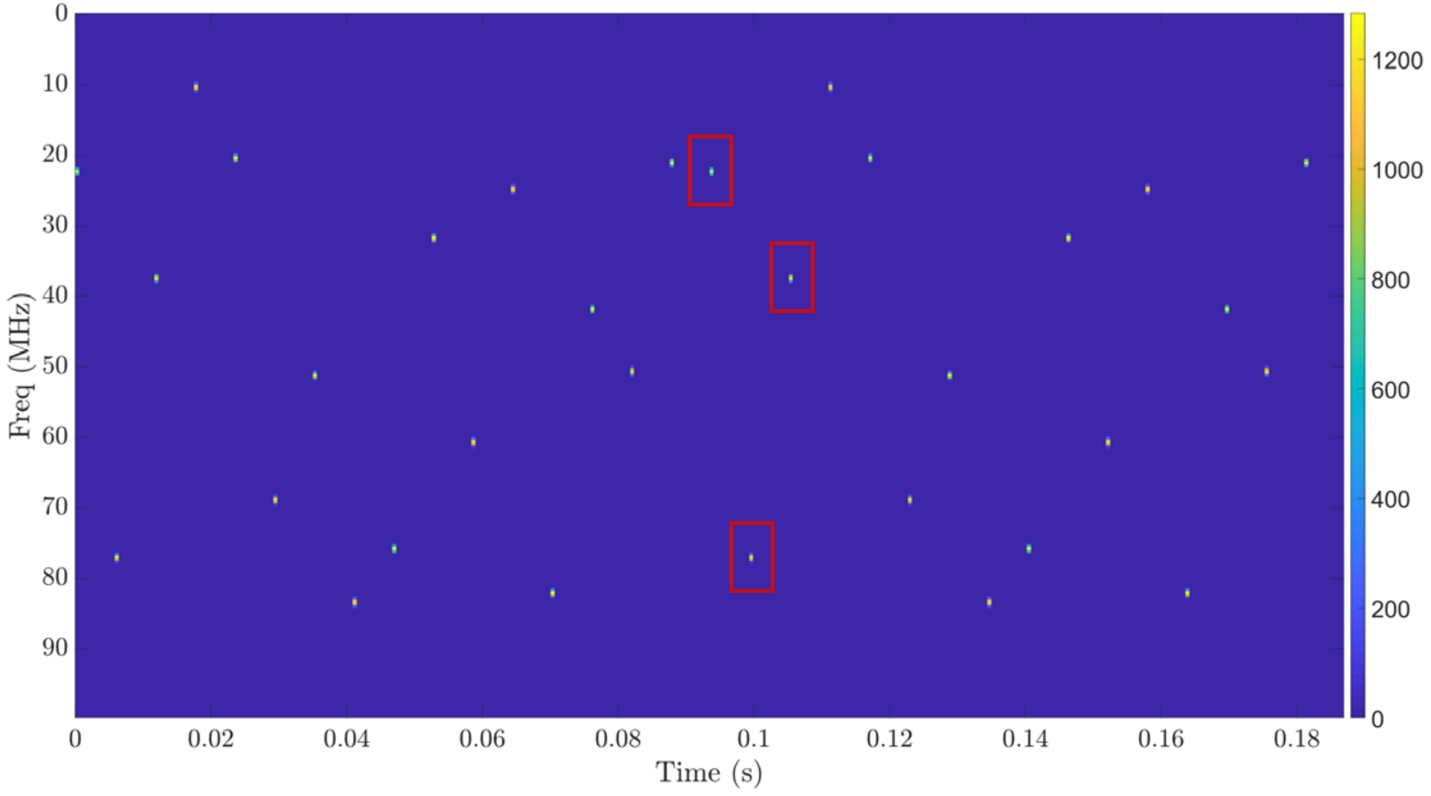
- Carrier frequency and bandwidth f_c, B;
- hopping pattern with 16 hops (96 ms);



FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

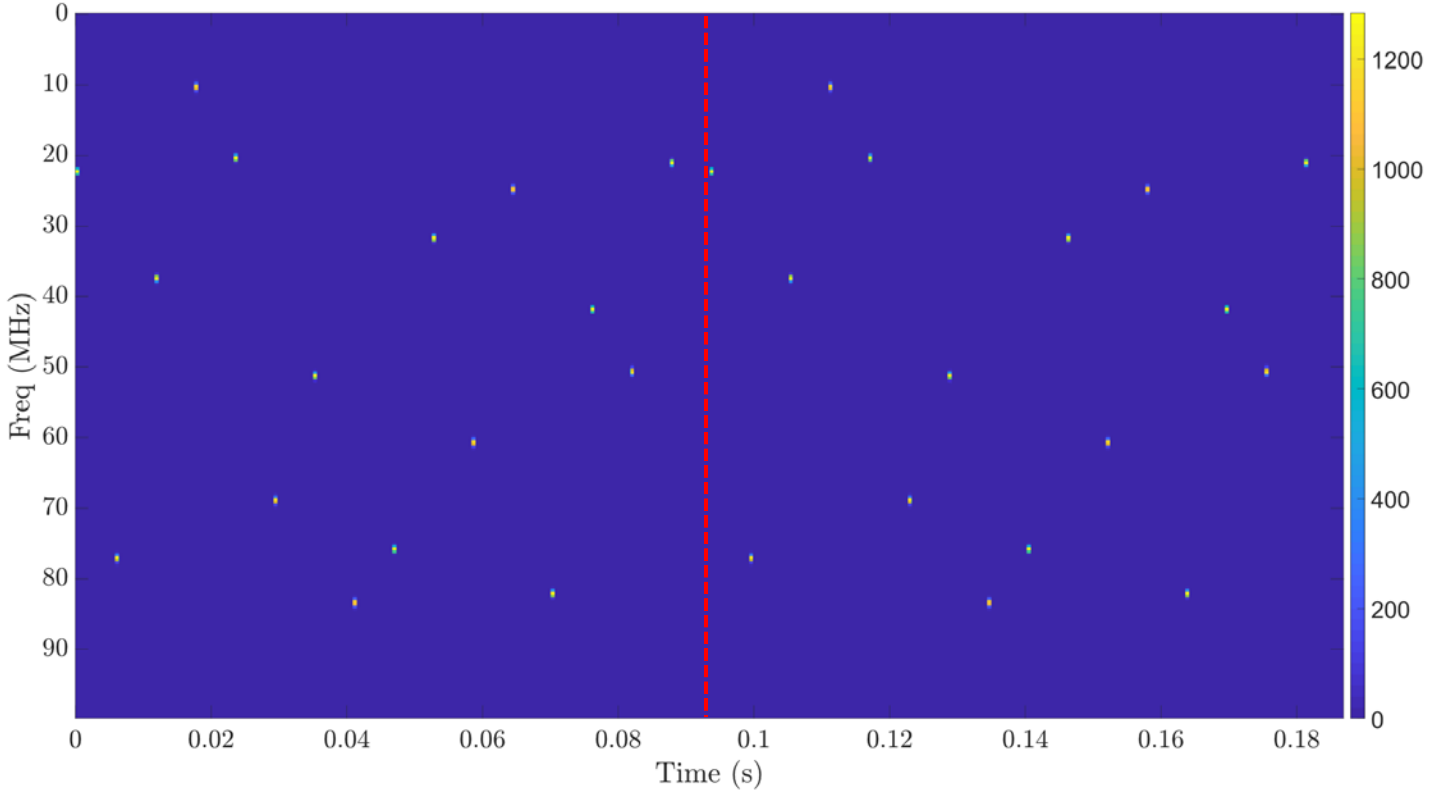
- Carrier frequency and bandwidth f_c, B;
- hopping pattern with 16 hops (96 ms);



FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

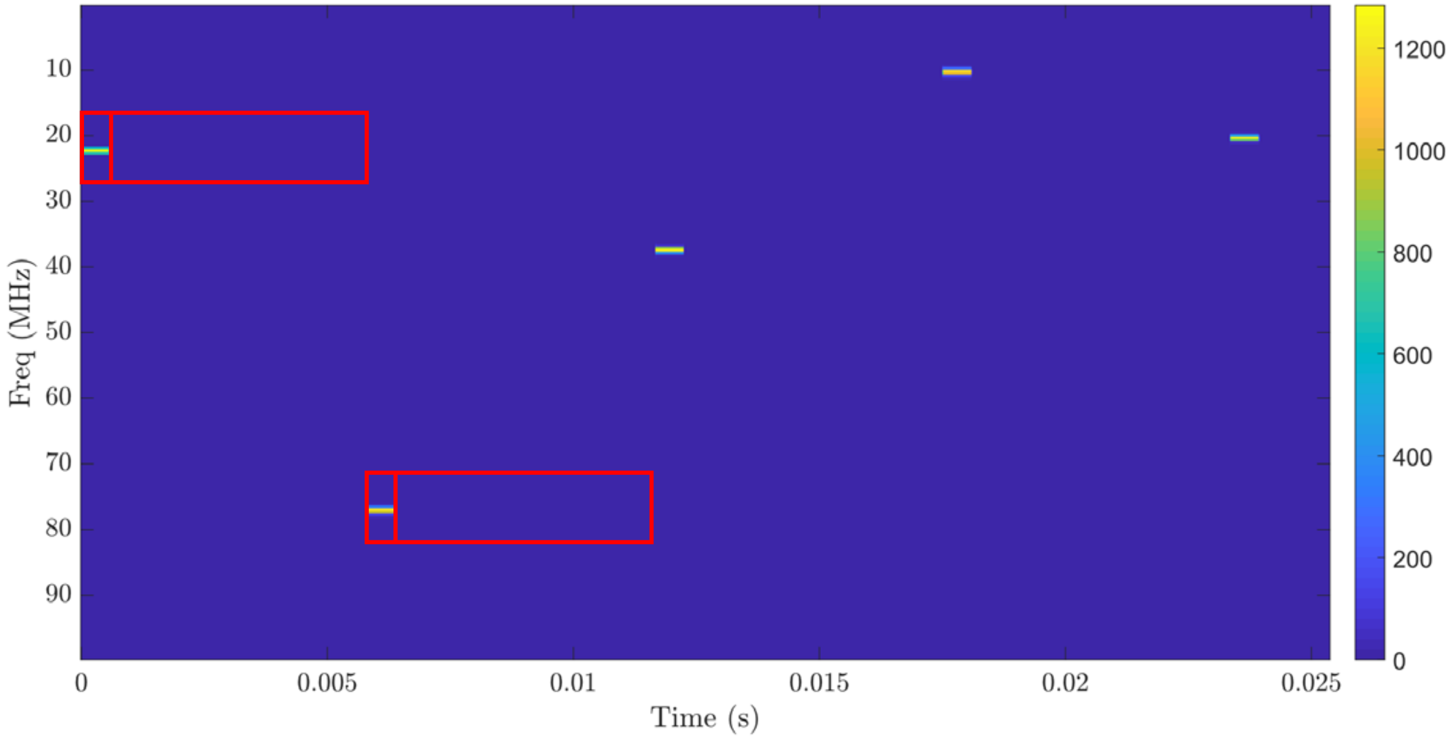
- Carrier frequency and bandwidth f_c, B;
- hopping pattern with 16 hops (96 ms);



FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

- Carrier frequency and bandwidth f_c, B;
- hopping pattern with 16 hops (96 ms);
- Dwell-Time $T_d = 6$ ms (167 hops/s);
- Duty cycle $D = 0.1$



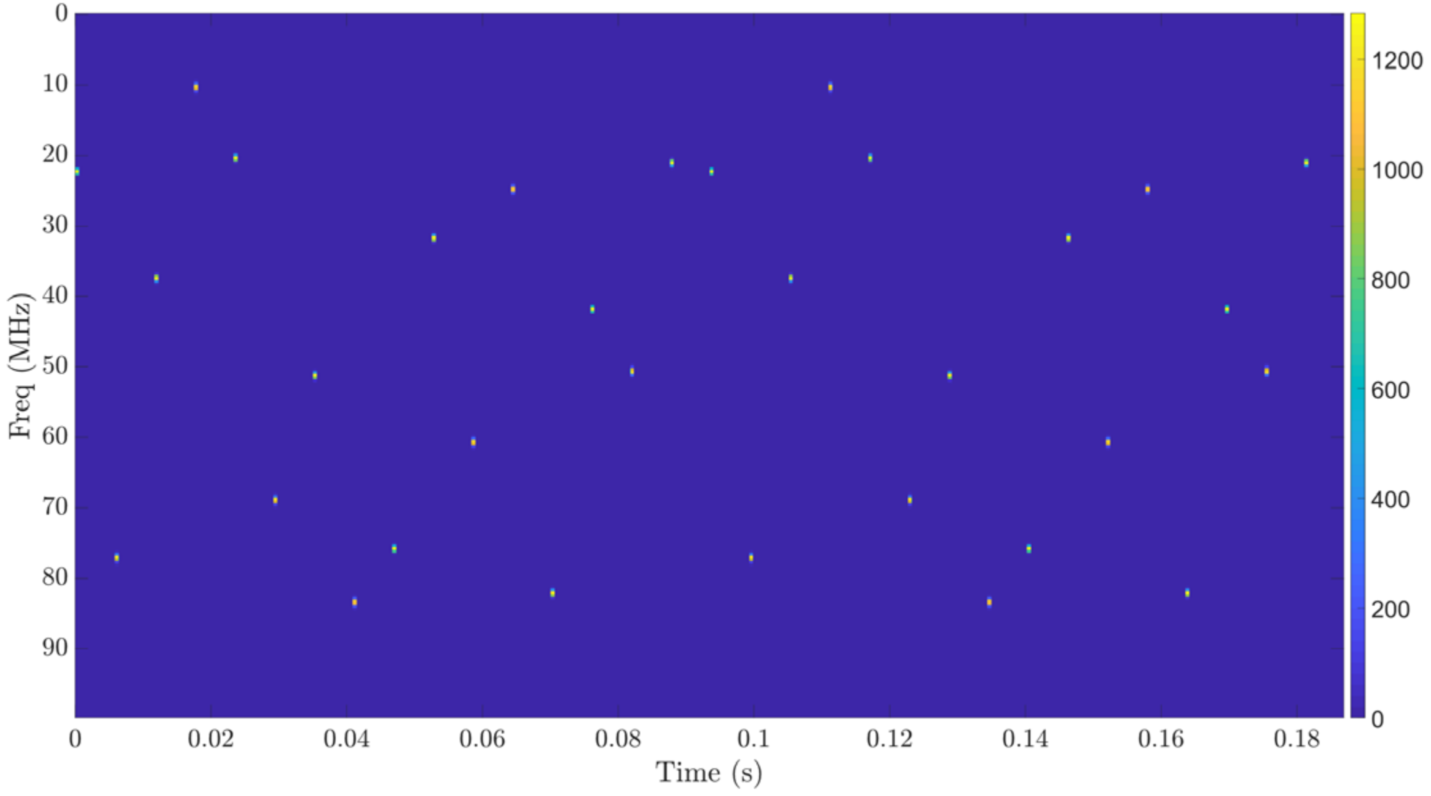
FHSS WAVEFORM
SIGNAL MODEL

FHSS WAVEFORM PARAMETERS

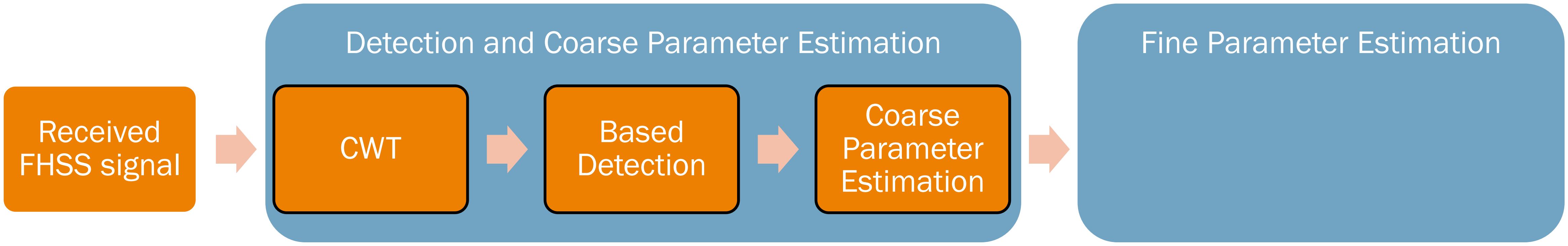
- Carrier frequency and bandwidth f_c, B;
- hopping pattern with 16 hops (96 ms);
- Dwell-Time $T_d = 6$ ms;
- Duty cycle $D = 0.1$

ASSUMPTIONS

- f_c and B are known and constant
- Fixed hopping pattern
- A single FHSS signal is presented at each time



RF LINK DETECTION AND CHARACTERIZATION
PARAMETRIC AND NON-PARAMETRIC METHODS



CWT-BASED DETECTION

- Detection of FHSS signal performed based on CWT
- A rough estimate of the hop time, dwell time, duty cycle and hopping pattern duration are provided

CWT-BASED FHSS DETECTION
CONTINUOUS WAVELET TRANSFORM

DETECTION PROBLEM

- Detect if an FHSS signal is present

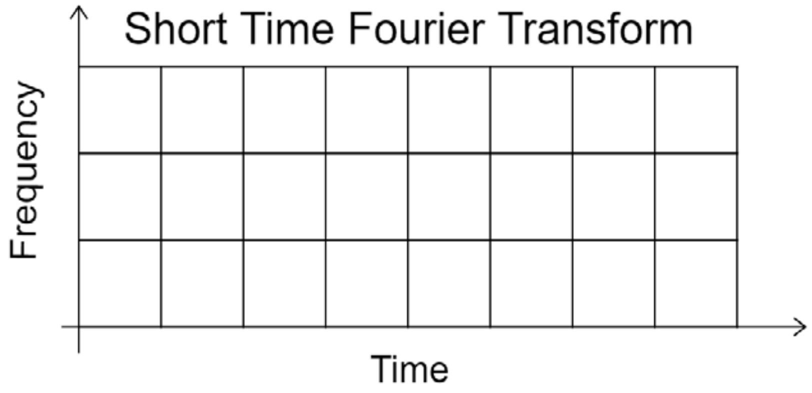
  $\mathcal{H}_0$: noise only
  $\mathcal{H}_1$: signal and noise

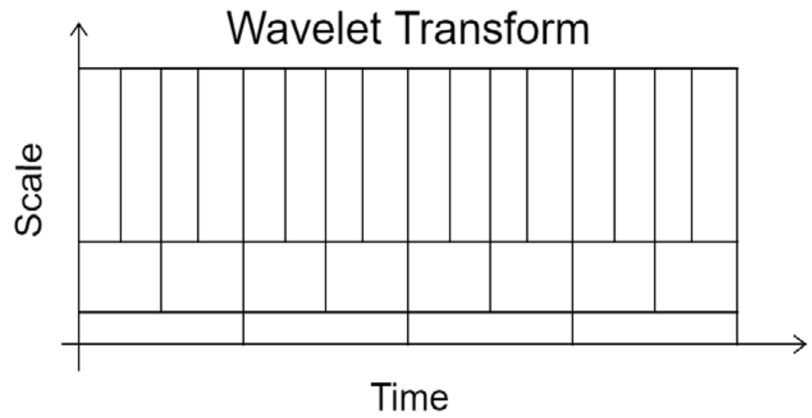
CONTINUOUS WAVELET TRANSFORM

- Captures both the slowly varying changes (hopping pattern) as the abrupt changes (single hops)

DETECTION PROCEDURE

- Detect peaks indicating hopping pattern, not individual hops.





CWT-BASED FHSS DETECTION
CONTINUOUS WAVELET TRANSFORM

DETECTION PROBLEM

- Detect if an FHSS signal is present

  $\mathcal{H}_0$: noise only
  $\mathcal{H}_1$: signal and noise

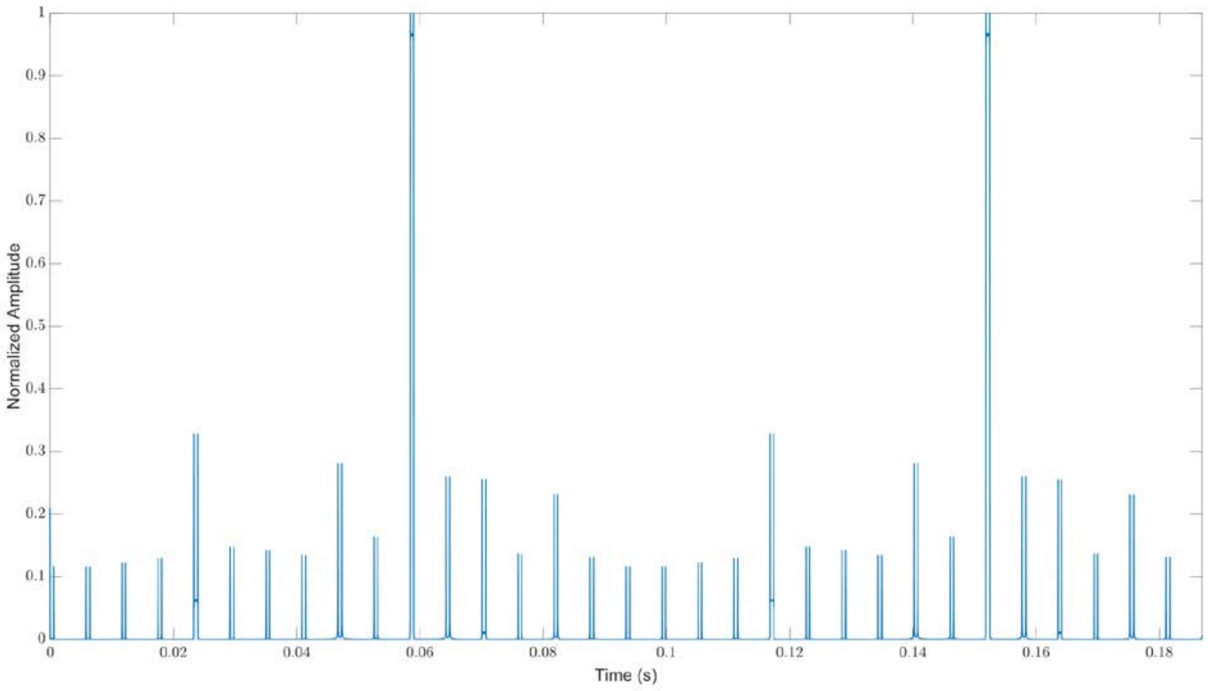
CONTINUOUS WAVELET TRANSFORM

- Captures both the slowly varying changes (hopping pattern) as the abrupt changes (single hops)

DETECTION PROCEDURE

- Detect peaks indicating hopping pattern, not individual hops.

Mean of wavelet coefficients



CWT-BASED FHSS DETECTION
CONTINUOUS WAVELET TRANSFORM

DETECTION PROBLEM

- Detect if an FHSS signal is present

  $\mathcal{H}_0$: noise only
  $\mathcal{H}_1$: signal and noise

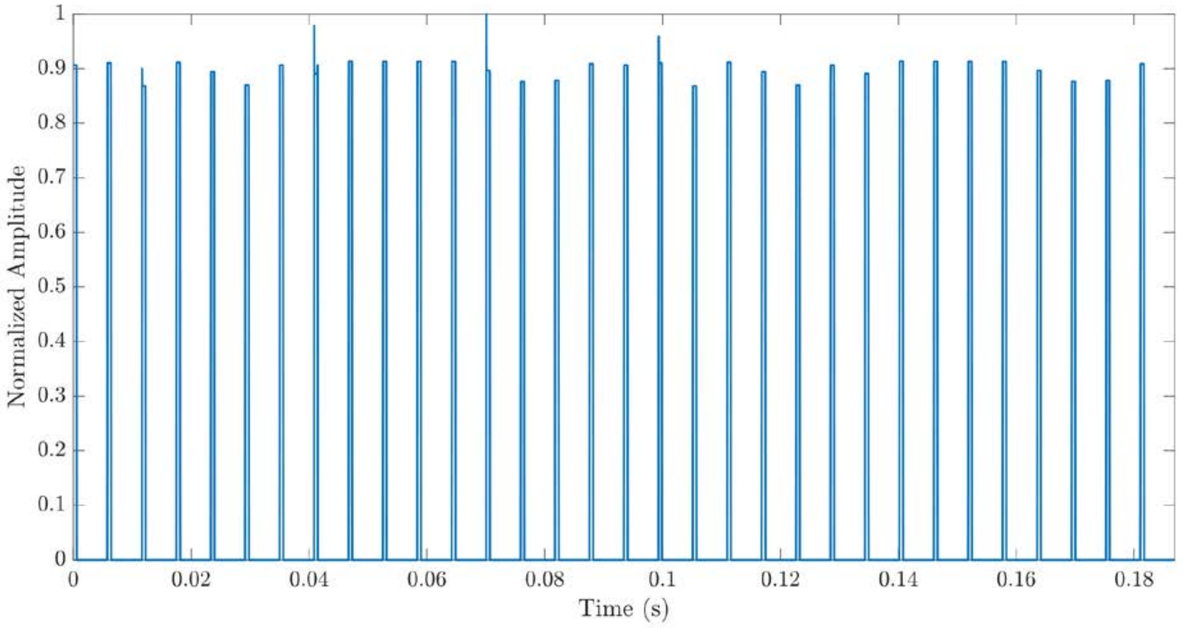
CONTINUOUS WAVELET TRANSFORM

- Captures both the slowly varying changes (hopping pattern) as the abrupt changes (single hops)

DETECTION PROCEDURE

- Detect peaks indicating hopping pattern, not individual hops.

Mean of Fourier coefficients



CWT-BASED FHSS DETECTION
CONTINUOUS WAVELET TRANSFORM

DETECTION PROBLEM

- Detect if an FHSS signal is present

  $\mathcal{H}_0$: noise only
  $\mathcal{H}_1$: signal and noise

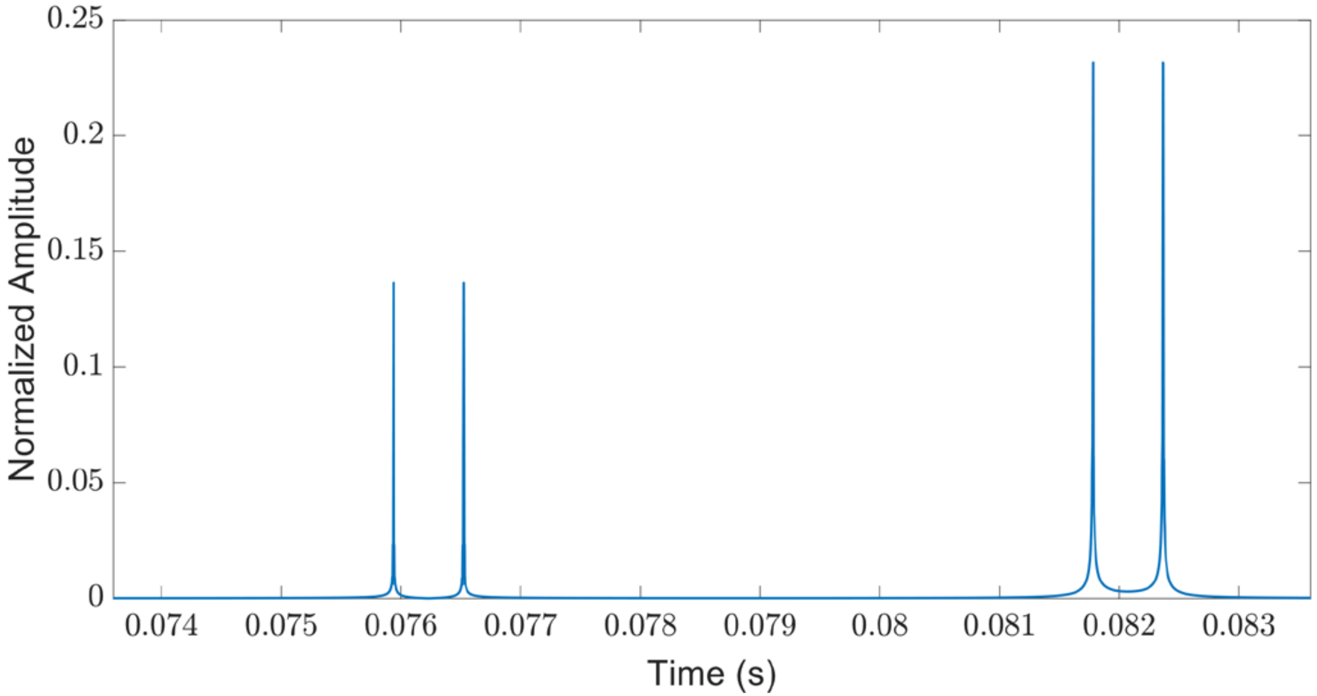
CONTINUOUS WAVELET TRANSFORM

- Captures both the slowly varying changes (hopping pattern) as the abrupt changes (single hops)

DETECTION PROCEDURE

- Detect peaks indicating hopping pattern, not individual hops.

Mean of wavelet coefficients: two hops



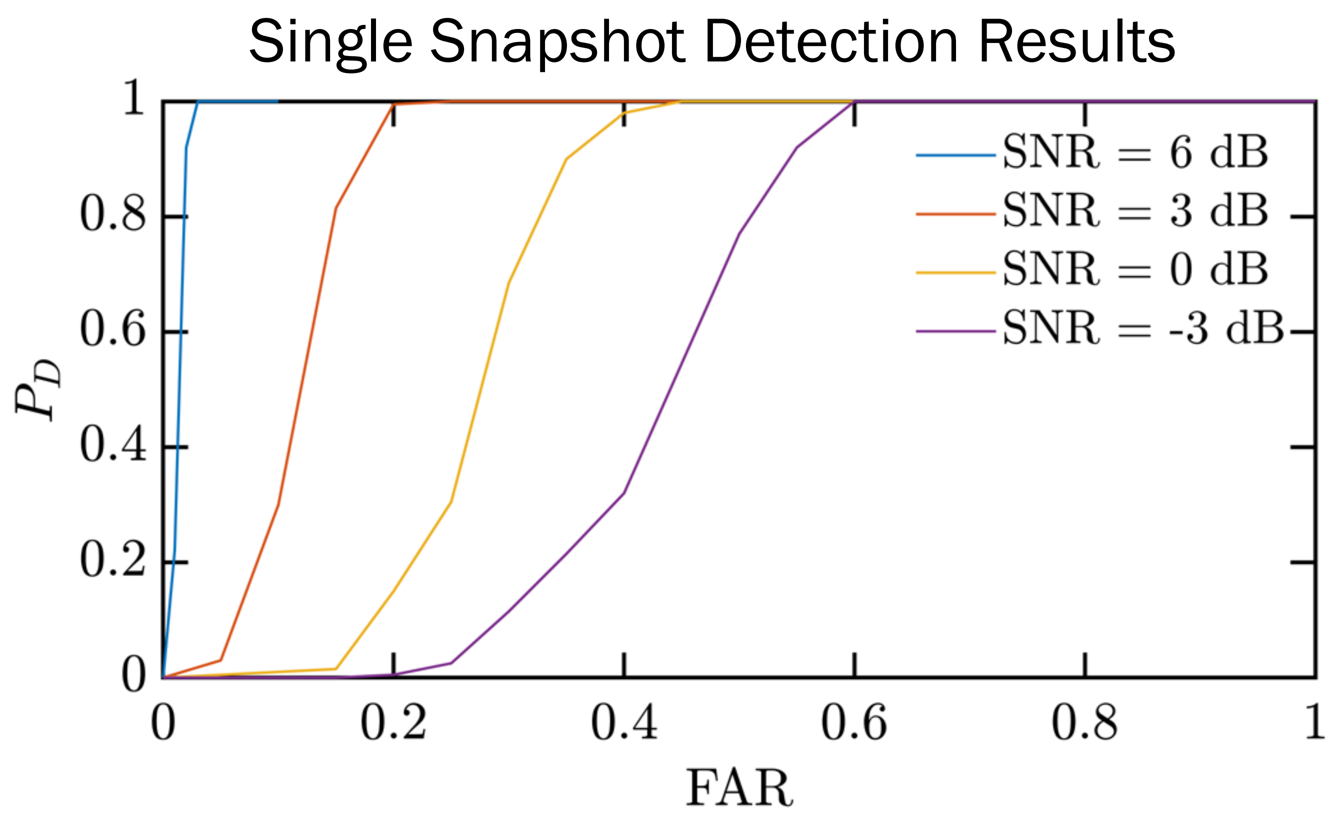
CWT-BASED FHSS DETECTION
RESULTS

SCENARIO

- Single FHSS signal in AWGN
- Range of SNR regimes
- Single snapshot (two hopping sequences)

MULTIPLE SNAPSHOTS

- Single snapshot, relatively low integration time
- Realistic observation time is larger



CWT-BASED FHSS DETECTION
SUMMARY

CWT-BASED DETECTION

- Captures both the slowly varying changes (hopping pattern) as the abrupt changes (single hops)
- Enables detection of FHSS signals

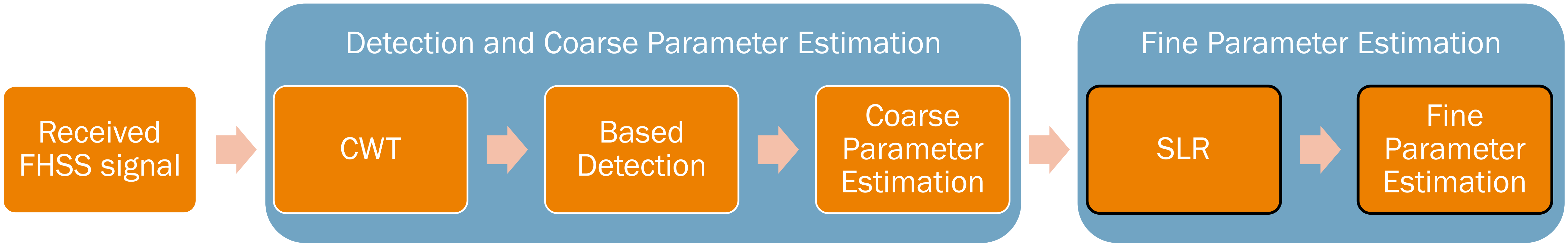
LIMITATIONS

- Differentiate between FHSS and other signal types
- Practical problem of multiple signals present at the same time

POSSIBLE SOLUTIONS

- ML approach; performs both detection and classifications.
- i.e. known with high probability if the received signal is indeed FHSS modulated.

RELATIONSHIP BETWEEN CWT AND SLR
NON – PARAMETRIC AND PARAMETRIC



CWT-BASED DETECTION

- Detection of FHSS signal performed based on CWT
- A rough estimate of the hop time, dwell time, duty cycle and hopping pattern duration are provided

SLR-BASED RF LINK CHARACTERIZATION

- Initialize using coarse bandwidth CWT estimate
- Fine estimation of signal parameters

SLR-BASED FHSS PARAMETER ESTIMATION
SPARSE LINEAR REGRESSION

SPARSE LINEAR REGRESSION*

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \|\mathbf{Y}_K - \mathbf{M}\boldsymbol{\theta}\|_F - \lambda_1 \|\boldsymbol{\theta}\|_1 - \lambda_2 \|\mathbf{D}\boldsymbol{\theta}\|_1$$

- A sparse representation of Time-Frequency distribution (TFD) is estimated from the time samples
- $\boldsymbol{\theta}$ represents samples of the TFD of the signal
- First term is a standard data matching least squares

* D. Angelosante, G. B. Giannakis and N. D. Sidiropoulos, "Estimating multiple frequency-hopping signal parameters via sparse linear regression," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5044-5056 (2010).

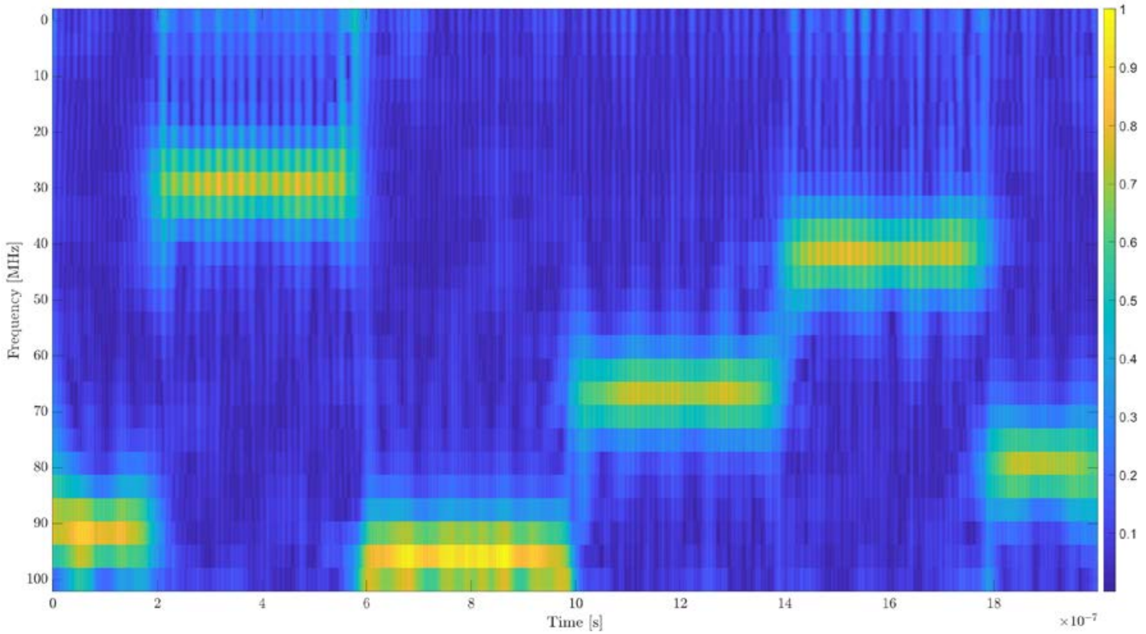
SLR-BASED FHSS PARAMETER ESTIMATION
SPARSE LINEAR REGRESSION

SPARSE LINEAR REGRESSION*

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \|\mathbf{Y}_K - \mathbf{M}\boldsymbol{\theta}\|_F - \lambda_1 \|\boldsymbol{\theta}\|_1 - \lambda_2 \|\mathbf{D}\boldsymbol{\theta}\|_1$$

- A sparse representation of TFD is estimated from the time samples
- $\boldsymbol{\theta}$ represents samples of the Time-Frequency distribution (TFD) of the signal

- First term is a standard data matching least squares
- Sparsity in frequency is controlled by λ_1



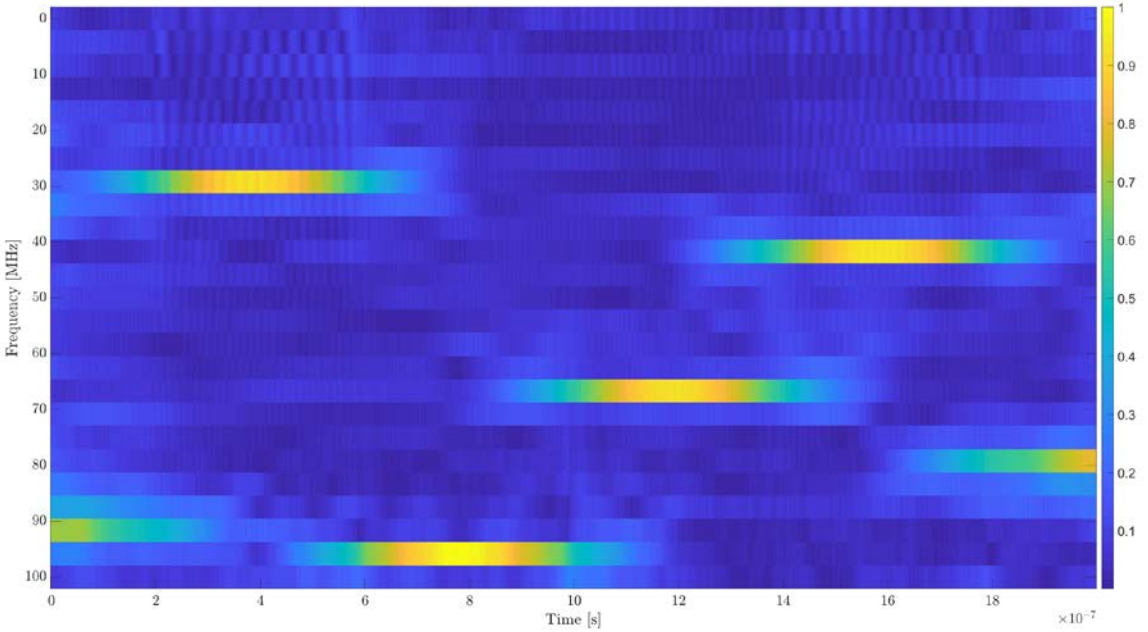
* D. Angelosante, G. B. Giannakis and N. D. Sidiropoulos, "Estimating multiple frequency-hopping signal parameters via sparse linear regression," *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5044-5056 (2010).

SPARSE LINEAR REGRESSION

SPARSE LINEAR REGRESSION*

$$\hat{\boldsymbol{\theta}} = \arg\min_{\boldsymbol{\theta}} \|\mathbf{Y}_K - \mathbf{M}\boldsymbol{\theta}\|_F - \lambda_1 \|\boldsymbol{\theta}\|_1 - \lambda_2 \|\mathbf{D}\boldsymbol{\theta}\|_1$$

- A sparse representation of TFD is estimated from the time samples
- $\boldsymbol{\theta}$ represents samples of the Time-Frequency distribution (TFD) of the signal



- First term is a standard data matching least squares
- Sparsity in frequency is controlled by λ_1
- Sparsity (of transitions) in time is controlled by λ_2

* D. Angelosante, G. B. Giannakis and N. D. Sidiropoulos, “Estimating multiple frequency-hopping signal parameters via sparse linear regression,” *IEEE Trans. Signal Process.*, vol. 58, no. 10, pp. 5044-5056 (2010).

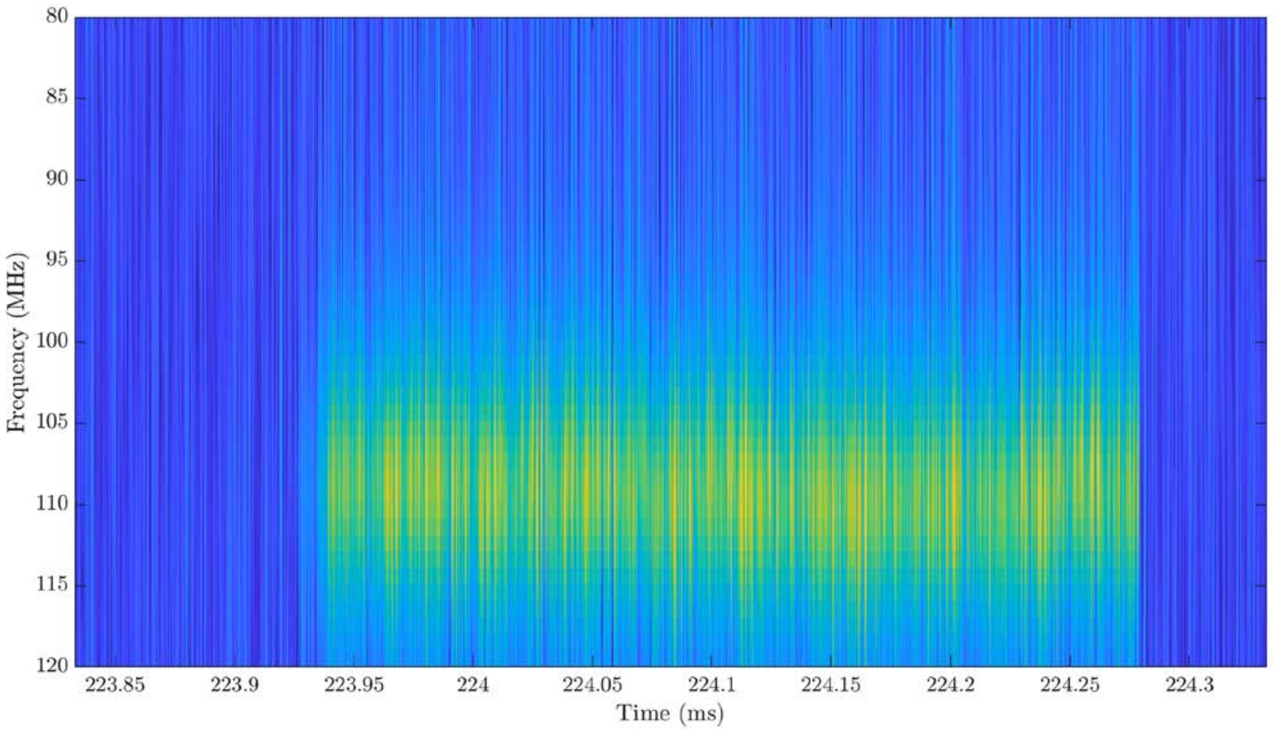
SLR-BASED FHSS PARAMETER ESTIMATION
RESULTS

SCENARIO

- Single hop from FHSS sequence
- SNR 20 dB

DISCUSSION

- Super resolution time-frequency estimate can be obtained based on SLR
- Resolution vs processing trade-off



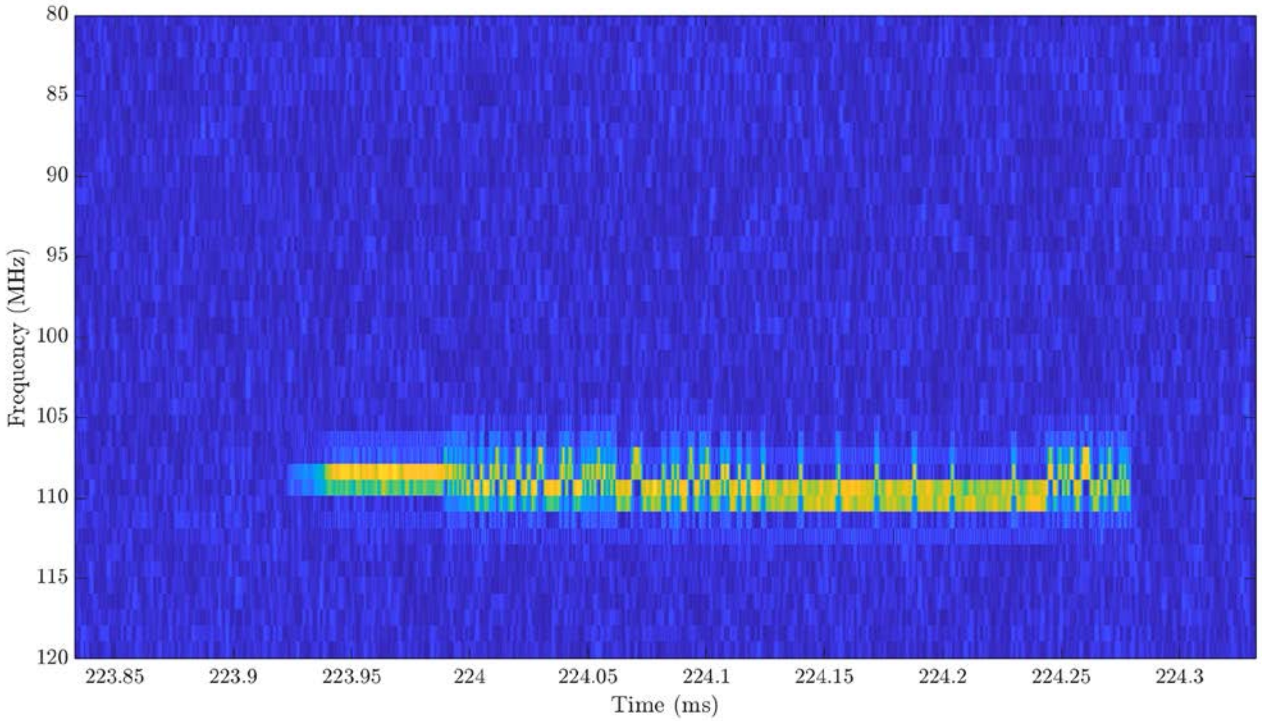
SLR-BASED FHSS PARAMETER ESTIMATION
RESULTS

SCENARIO

- Single hop from FHSS sequence
- SNR 20 dB

DISCUSSION

- Super resolution time-frequency estimate can be obtained based on SLR
- Resolution vs processing trade-off

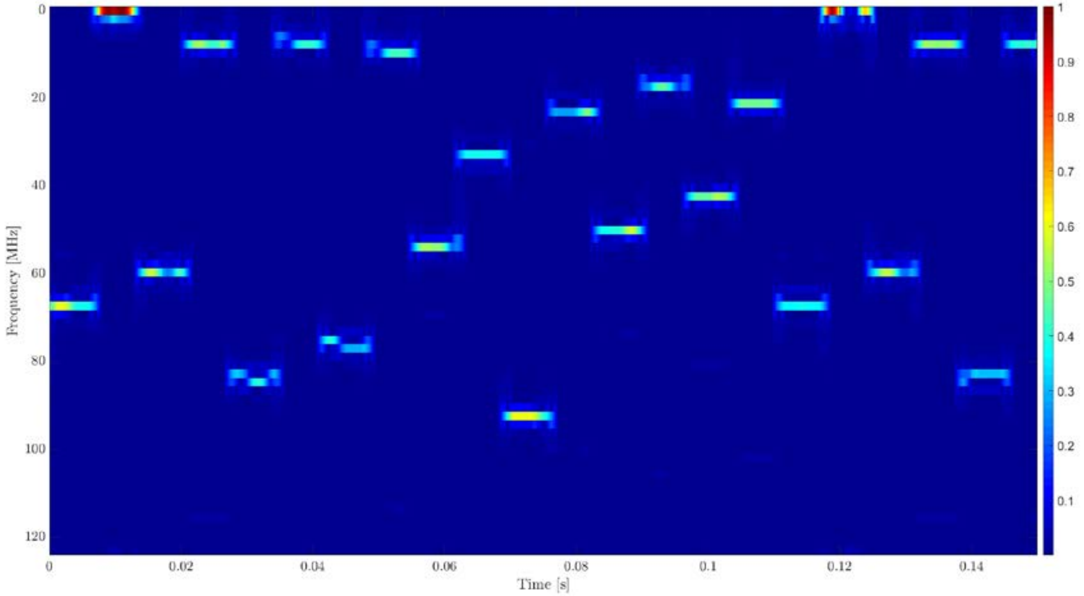


CHALLENGES IMPLEMENTING SLR
BIG DATA VOLUME

SPARSE LINEAR REGRESSION

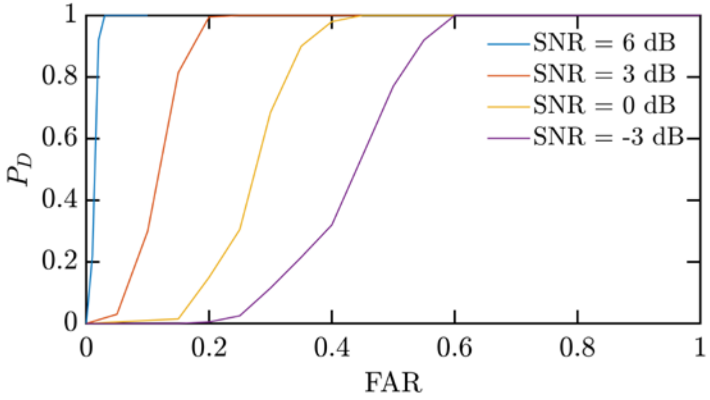
- The data matrix $\mathbf{Y}_K$ is constructed by full over-segmentation of the data
  - The sampling rate is relatively high (hundreds of MHz)
  - Large system of equations must be solved (at each iteration)
- Both the mixing matrix $\mathbf{M}$, and the unknown vector $\boldsymbol{\theta}$ are (block) sparse
  - MinresQLP as a candidate Krylov subspace based solver is used
  - Operations involving the matrices $\mathbf{M}$ and $\mathbf{D}$ are implemented as subroutines (to avoid large memory requirements)
- Results from detection methods are used to reduce data volume

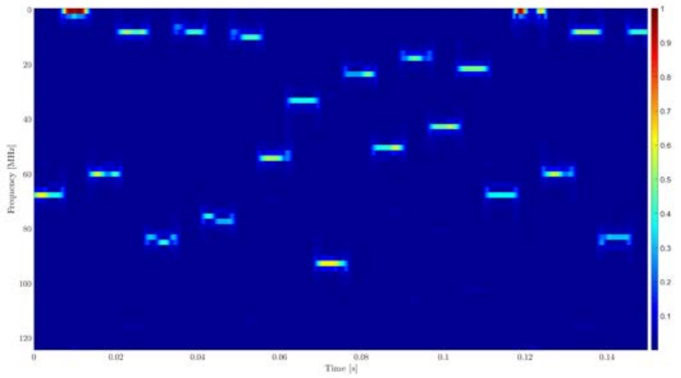
Processing time ~10 minutes for $N = 13000$ samples on a typical laptop (e.g. Pentium i7 with 12GB memory).



SUMMARY
DETECTION AND FHSS PARAMETER ESTIMATION

Received FHSS signal → **Detection and Coarse Parameter Estimation**: CWT → Based Detection → Coarse Parameter Estimation → **Fine Parameter Estimation**: SLR → Fine Parameter Estimation





FUTURE WORK

- Detection and classification
  - Demonstrate machine Learning based detection and classification of multiple signal types in simulation environment
- Counter Measures
  - Jamming selective in time and frequency with low transmit power
  - Demonstrate feasibility and effectiveness of selective jamming in lab environment
- Multiple targets and harsh transmission environments
  - Exploiting spectral diversity
  - Source separation (e.g. based on direction finding)

ACKNOWLEDGEMENTS

- Joint counter UAS knowledge build-up program financed by the Netherlands Ministry of Defence and the National Police

Ministerie van Defensie

POLITIE