Carrier Frequency Offset Estimation Methods

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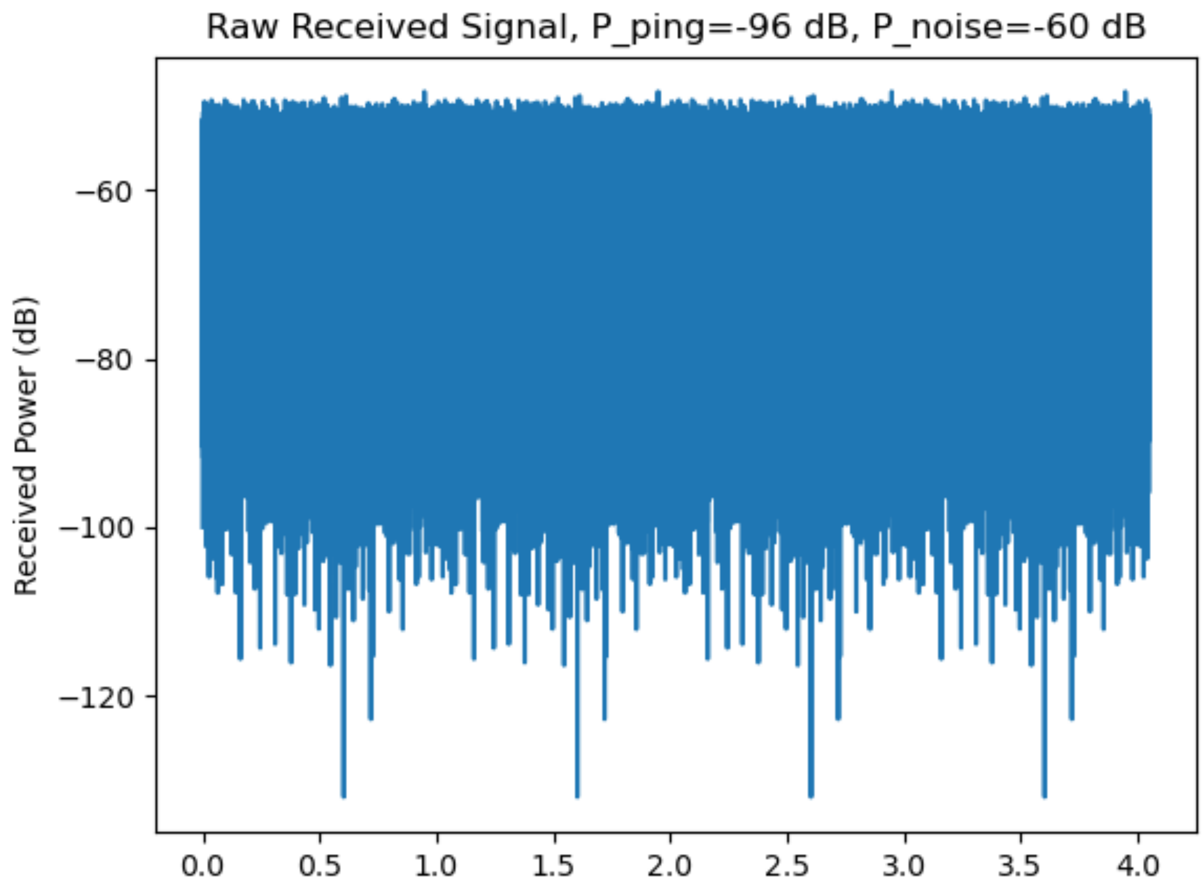
Signal Processing Fundamentals Utilized

- The covered methods involve: Angle of Mean (**AOM**) or Mean of Angle (**MOA**) for signal samples with or without reusing (**R or NR**) of sampled data blocks, Maximum likelihood Estimates (**MLE**), Best Linear Unbiased Estimator (**BLUE**) and **Conventional CFO-E** (Carrier/Center Frequency Offset Estimates).
- The main conditions against which predictions are checked against are: **corrected phase error, mean squared error, standard deviation, Cramer-Rao (Lower) Bound, and Error Vector Magnitude.** These are metrics for testing in DSP commonly used.
- These conditions are statistical measures in DSP specifically used to measure performances of different estimator methodologies
- W=4 is utilized (non-logged variable, for B,Q effective mapping, as a functional hyperparameter)

Results against Test Signal

- This code was run against the generated test signal as described by code in "autocorrelation_tests.py" in the NH0 branch of the main repo. Simple plot of signal Power with time the signal is received for.

- The results indicate a 99.98% accuracy in prediction to the actual offset, along with additional analysis for best methods given certain conditions.



Results against Test Signal

- Shown are the .txt file snapshots of the data processing performed on the signal
- It covers experimental parameters, conditional analysis, and predictions with each method instantiation

```
Phase Wrap Offset, Common Phase Error (CPE) (rads):

AOM-NR: -0.893048012195208 rads
MOA-NR: -0.9426585905716819 rads
AOM-R: -0.5827265638879049 rads
MOA-R: -0.20824415357867687 rads
conventional: 1.1044256178783909 rads
MLE: 0.9819028565486231 rads
BLUE: -1.4976124600290182 rads

Estimated Offsets (CFO, or Carrier/Central Frequency Offsets) (Hz):

AOM-NR: 4999.402132486138 Hz
MOA-NR: 4999.938298536207 Hz
AOM-R: 4999.647846527413 Hz
MOA-R: 4999.859120277494 Hz
conventional: 4999.983290401241 Hz
MLE: 4999.360496872195 Hz
BLUE: 4999.999783219947 Hz

Legend:

AOM-NR=Angle of Mean, Non-Reuse
MOA-NR=Mean of Angle, Non-Reuse
AOM-R=Angle of Mean, Reuse
MOA-R=Mean of Angle, Reuse
MLE=Maximum Likelihood Estimate
BLUE=Best Linear unbiased Estimator

User Choice List of Experiment:

Signal Type for Experiments: test
B, Q Overwrite: True
Hyperparameter Hardsetting: True
Type of Noise applied to Signal: N/A
Signal Normalized with respect to Power: False
U Samples for EVM modeling: Signal Length
```

```
Logged Data From Experiment:

Hyper-parameters considered in this experimental run (CPE correction or CPE non-correction):

Sampling Frequency (Hz): 1000000
Carrier (Central) Frequency (Hz): 172000000
Frequency Offset to Guess (Hz): 5000
Ping Power (dB): -96
Noise Power (dB): -60
Pilot Block Length (P): 64
Pilot Block Length (M): 64
Data Block Length (N): 1024
Number of Frames (B): 8
Number of Frames (B', for Reuse): 9
Transmission Block Length (Q): 6464
Decimation Rate (ψ): 4
Backoff Rate (ignored) (D): 4

Summary (Assumed: Bias=0, Transmitted Signal = Received Signal; for all methods): Signal Type: test

Type of Analysis with Least MSE: MOA-NR, with a MSE (mean squared error) value of 1.3130337560179596e-18 Hz, which is 4999.938298536207 Hz for an actual offset of 5000 Hz
Type of Analysis with Least STD DEV: BLUE, with a standard deviation value of 0.00021678005305147963 Hz, which is 4999.999783219947 Hz for an actual offset of 5000 Hz
Type of Analysis with Least Cramer Rao Lower Bound: BLUE, with a CRLB value of 9.152816184041546e-21 Hz, which is 4999.999783219947 Hz for an actual offset of 5000 Hz
Type of Analysis with Least CPE Offset: MOA-R, with a corrected phase error value of -0.20824415357867687 rads, which is 4999.859120277494 Hz for an actual offset of 5000 Hz
Type of Analysis with Least EVM value: MLE, with a error vector magnitude value of 5.089563970267461e-05 dB, which is 4999.360496872195 Hz for an actual offset of 5000 Hz

MSE (Hz):

AOM-NR: 2.0258682844126846e-15 Hz
MOA-NR: 1.3130337560179596e-18 Hz
AOM-R: 6.0672427301133804e-18 Hz
MOA-R: 2.961540619199097e-07 Hz
conventional: 0.00027921069068701995 Hz
MLE: 0.4089642504727051 Hz
BLUE: 4.699359140100232e-08 Hz

STD DEV (Hz):

AOM-NR: 0.5978675138621838 Hz
MOA-NR: 0.06170146379281505 Hz
AOM-R: 0.352153472586906 Hz
MOA-R: 0.14087972250581515 Hz
conventional: 0.01670959875900735 Hz
MLE: 0.6395031278052556 Hz
BLUE: 0.00021678005305147963 Hz

Cramer-Rao Lower Bound (CRLB) (Hz):

AOM-NR: 7.238370576834694e-14 Hz
MOA-NR: 7.418066246513396e-16 Hz
AOM-R: 2.448631285419677e-14 Hz
MOA-R: 3.874090331363454e-15 Hz
conventional: 5.438280670314297e-17 Hz
MLE: 8.327233768323431e-14 Hz
BLUE: 9.152816184041546e-21 Hz

Error Vector Magnitude (EVM) (dB):

AOM-NR: 5.0895657563761654e-05 dB
MOA-NR: 5.0895887558091584e-05 dB
AOM-R: 5.08957629685664e-05 dB
MOA-R: 5.089585359525802e-05 dB
conventional: 5.089590685672577e-05 dB
MLE: 5.089563970267461e-05 dB
BLUE: 5.0895913931047256e-05 dB
```

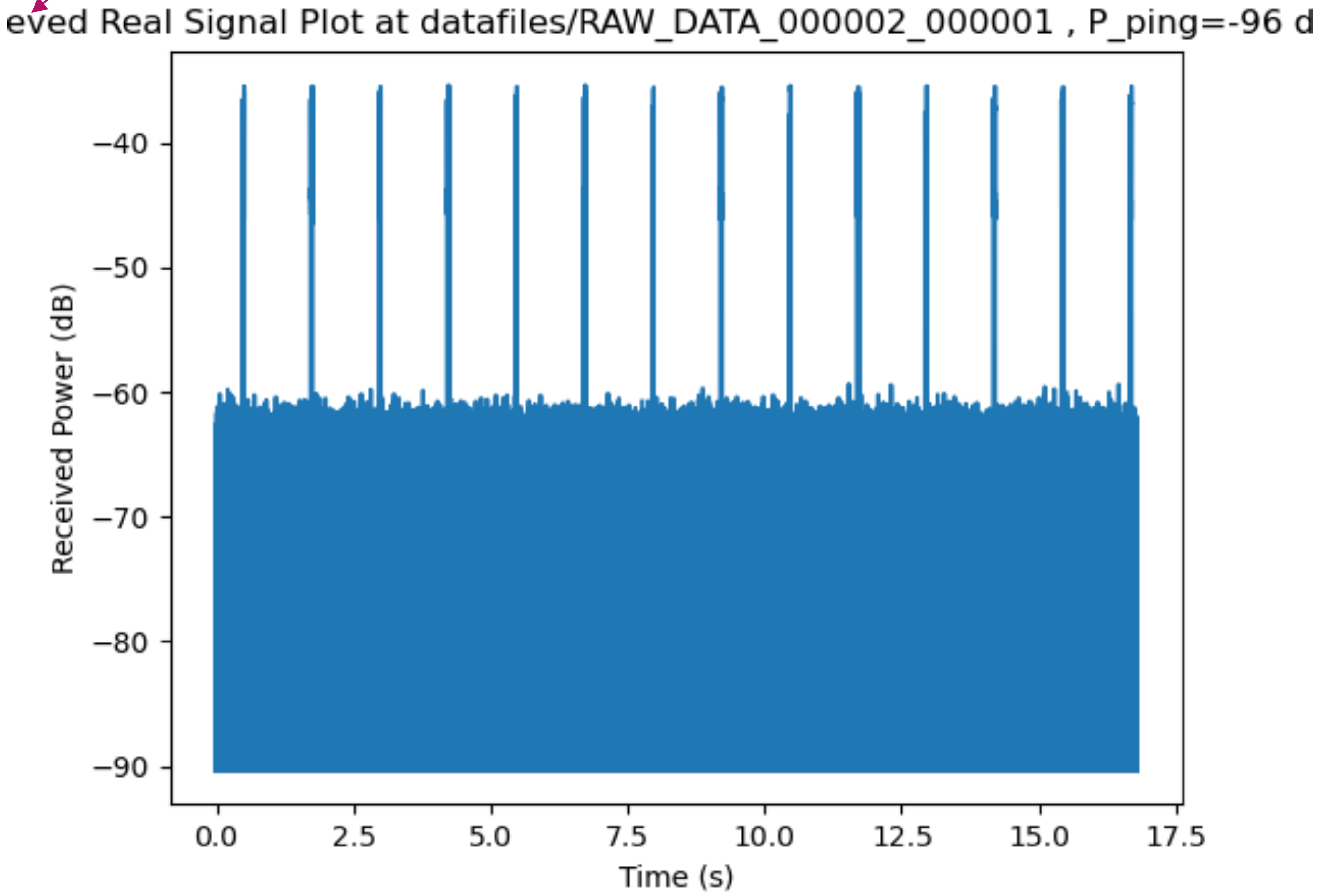
Zoom in to view details ^

Results against Real Signal

- This code was run against the real signal as read from the RAW data binary taken from the drone by Mia. Simple plot of signal Power with time the signal is received for.

- The results indicate a 99.98% accuracy in prediction to the actual offset, along with additional analysis for best methods given certain conditions. (Same as test signal, with different predicted magnitudes)

Received



Results against Real Signal

- Shown are the .txt file snapshots of the data processing performed on the signal
- It covers experimental parameters, conditional analysis, and predictions with each method instantiation

```
Phase Wrap Offset, Common Phase Error (CPE) (rads):

AOM-NR: -0.6352716874327206 rads
MOA-NR: -0.7938149162046036 rads
AOM-R: 1.0072756645542478 rads
MOA-R: 0.9817948277915589 rads
conventional: 0.8773992669271766 rads
MLE: 1.1697206127526552 rads
BLUE: 0.11231268516267674 rads

Estimated Offsets (CFO, or Carrier/Central Frequency Offsets) (Hz):

AOM-NR: 4999.622766027007 Hz
MOA-NR: 4999.89190457509 Hz
AOM-R: 4999.403725784692 Hz
MOA-R: 4999.992319771537 Hz
conventional: 4999.985734406843 Hz
MLE: 4999.250417203713 Hz
BLUE: 4999.999821622719 Hz

Legend:

AOM-NR=Angle of Mean, Non-Reuse
MOA-NR=Mean of Angle, Non-Reuse
AOM-R=Angle of Mean, Reuse
MOA-R=Mean of Angle, Reuse
MLE=Maximum Likelihood Estimate
BLUE=Best Linear unbiased Estimator

User Choice List of Experiment:

Signal Type for Experiments: real
B, Q Overwrite: True
Hyperparameter Hardsetting: True
Type of Noise applied to Signal: N/A
Signal Normalized with respect to Power: False
U Samples for EVM modeling: Signal Length
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```
Logged Data From Experiment:

Hyper-parameters considered in this experimental run (CPE correction or CPE non-correction):

Sampling Frequency (Hz): 1000000
Carrier (Central) Frequency (Hz): 172000000
Frequency Offset to Guess (Hz): 5000
Ping Power (dB): -96
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Pilot Block Length (P): 64
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Number of Frames (B): 8
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Transmission Block Length (Q): 6464
Decimation Rate (ψ): 4
Backoff Rate (ignored) (D): 4

Summary (Assumed: Bias=0, Transmitted Signal = Received Signal; for all methods): Signal Type: real

Type of Analysis with Least MSE: MOA-NR, with a MSE (mean squared error) value of 1.2538499739628677e-17 Hz, which is 4999.89190457509 Hz for an actual offset of 5000 Hz
Type of Analysis with Least STD DEV: BLUE, with a standard deviation value of 0.00017837728137237718 Hz, which is 4999.999821622719 Hz for an actual offset of 5000 Hz
Type of Analysis with Least Cramer Rao Lower Bound: BLUE, with a CRLB value of 6.1971953241954094e-21 Hz, which is 4999.999821622719 Hz for an actual offset of 5000 Hz
Type of Analysis with Least CPE Offset: BLUE, with a corrected phase error value of 0.11231268516267674 rads, which is 4999.999821622719 Hz for an actual offset of 5000 Hz
Type of Analysis with Least EVM value: MLE, with a error vector magnitude value of 1.3020449286771055e-05 dB, which is 4999.250417203713 Hz for an actual offset of 5000 Hz

MSE (Hz):

AOM-NR: 2.651633169133331e-16 Hz
MOA-NR: 1.2538499739628677e-17 Hz
AOM-R: 1.3148626536162737e-16 Hz
MOA-R: 2.9615411247293635e-07 Hz
conventional: 0.0002035071481147335 Hz
MLE: 0.5618743684888857 Hz
BLUE: 3.181845450980022e-08 Hz

STD DEV (Hz):

AOM-NR: 0.3772339729930536 Hz
MOA-NR: 0.10809542491006141 Hz
AOM-R: 0.596274215307858 Hz
MOA-R: 0.007680228462959349 Hz
conventional: 0.014265593156778777 Hz
MLE: 0.7495827962866315 Hz
BLUE: 0.00017837728137237718 Hz

Cramer-Rao Lower Bound (CRLB) (Hz):

AOM-NR: 2.8154700752032736e-14 Hz
MOA-NR: 2.2787369936098466e-15 Hz
AOM-R: 7.198377989292887e-14 Hz
MOA-R: 1.1488603110607062e-17 Hz
conventional: 3.963743931769357e-17 Hz
MLE: 1.1626683400092138e-13 Hz
BLUE: 6.1971953241954094e-21 Hz

Error Vector Magnitude (EVM) (dB):

AOM-NR: 1.302048784084898e-05 dB
MOA-NR: 1.3020515706447683e-05 dB
AOM-R: 1.3020465161134253e-05 dB
MOA-R: 1.3020526102677366e-05 dB
conventional: 1.3020525420884907e-05 dB
MLE: 1.3020449286771055e-05 dB
BLUE: 1.3020526879353883e-05 dB
```

Zoom in to view details ^

Programming Overview

- The code uses a CLI (Command Line Interface) to ask the user certain experimental parameters, which aid in finetuning specific processes performed, leading to slightly different estimates, within the same aforementioned accuracy range.
- The code is fully written in python 3.8+ and utilizes the certain dependencies (see later) for mathematical analysis, depiction and optimization
- The code is self contained within 1 file, and also utilizes file I/O to specified folders
- Matplotlib is another plot and image processing dependency used that writes to specified folders, for signal plots.

Programming Overview: User Inputs

- For the terminal-based inputs for used prompting when navigated to the directory with the code with filename “offset_est.py” and running it, please adhere to the given user input choices, and advice.
- Follow the advice in the CLI prompt for experimental options of hyperparameter setting, computation of hyperparameters, noise addition, normalization, and EVM sampling.

- **Further notes on results with these inputs:**
- The results are consistent for real and test data, with a very high value of accuracy from the given aim of Center Frequency Offset(at minimum) (4999/5000)x100%=~99.98%

- The results are explained in detail with abbreviations, metrics and values in the txt file containing them.

Dependencies

- The code has the following dependencies (latest versions via pip installs):

- Scipy: for integration
- Numpy: for mathematical computations
- Matplotlib: signal plotting
- Struct: real data binary reads
- os: file path traversal for raw data access
- Datetime, time, warnings: minor resolution handling

References

- The mathematics behind DSP in this code is in accordance to the processes described in:
- The novel journal paper: **"High Resolution Carrier Frequency Offset Estimation in Time-Reversal Wideband Communications, Chen Et. Al. (University of Maryland), IEEE Transactions on Communications, 2018"** Link: http://sig.umd.edu/publications/Chen_CFOest.pdf
- And, the conference paper for the same (abridged): **"Accurate Carrier Frequency Offset Estimation in Time-Reversal Communications, Chen Et. Al. (University of Maryland), 2015 IEEE GlobalSIP"** Link: http://sig.umd.edu/publications/Chen_globalsip_2015.pdf
- Other knowledge such as conventional or BLUE methods is ubiquitously known in Signal Processing (I can still provide common resources for them if needed)