An Evaluation of Adaptive Equalizers on Non-Linear HF/Ionospheric Channel Models

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Outline

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- DFE
- Equalizers Under Test (LMS & CMA)
- Channel Models
- Results
- Conclusions / Next Steps

Introduction

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High Frequency (3-30 MHz) Band

- Enable long-range communications without significant channel architecture.
- Reflect signals off of ionosphere, no additional equipment required. Enables low-cost communications.
- Lack of equipment also makes High Frequency (HF) systems more reliable in the event of major systematic failure.

Problem Statement

- Ionosphere is unstable medium, constantly fluctuating due to changes in atmospheric conditions:
  - Solar Radiation
  - Seasonal Changes
  - Time of Day
- Ionospheric models, like the Watterson model, have been developed to simulate this behavior but assume that the channel is:
  - Stationary in time and frequency
  - Accurate for small bandwidths
  - Don’t capture non-linear effects.

Objective

- Equalizers can be used in the receiver to recover the corrupted signal.
- Adaptive equalization: error between this estimated and transmitted signal is fed into a learning algorithm to adjust the equalizer's coefficients.
- Compare the performance of two adaptive equalizers in the HF channel in linear and non-linear channel models:
  - Least Mean Squares Decision Feedback Equalizer (i.e. LMS-DFE)
  - Constant Modulus Algorithm (CMA) Equalizer

Background

Previous HF Equalization Efforts

- [7] showed that a Decision-Feedback equalizer (DFE) is better suited for the HF channel than maximum-likelihood sequence estimation (MLSE) equalizers.
- Different DFE’s implemented over the past few decades:
  - LMS-DFE
  - RLS-DFE
  - Kalman-DFE (using LMS and/or RMS as learning algorithm)
- Blind Equalization
- Turbo Equalization

Decision-Feedback Equalizer (DFE)

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DFE Functionality

- Consists of a Feed-Forward and Feedback filter.

$$\hat{\boldsymbol{I}}_{\mathrm{k}} = \sum_{j=-K_1}^{0} c_j v_{k-j} + \sum_{j=1}^{K_2} c_j \check{\boldsymbol{I}}_{k-j}$$

Feed-forward filter

Feedback filter

- J and c_j and represent the taps of the DFE.
- V represents the sequences received from the channel.
- $\check{I}_{\mathrm{k}}$ represents symbols decoded in previous iterations.
- $\hat{I}_{\mathrm{k}}$ represents the output of the equalizer.

DFE Functionality

- Can use MSE as learning algorithm to adjust the taps.
- Cost Function

$$J(K_1, K_2) = E|I_k - \hat{I}_k|^2$$

- K_1 and K_2 represent the number of taps of the feed-forward and feedback filters.

Least Means Squares and Constant Modulus Algorithms

LMS Algorithm

$$e(n) = d(n) - y(n)$$

$$y(n) = \hat{w}^H(n)u(n)$$

- e(n) represents error
- d(n) represents desired response
- y(n) represents equalized output
- $\hat{w}(n)$ represents estimate of ideal weight vector w.
- H represents Hermitian operator
- u(n) represents input sequence.

LMS Algorithm

- LMS algorithm minimizes following cost function:

$$\mathrm{J}(\mathrm{n}) = \mathrm{E}[|e(n)|^2] \sim e(n)e^*(n)$$

- Update equation given by the following:

$$\widehat{w}(n+1) = \widehat{w}(n) + \mu u(n)e^*(n)$$

- µ represents step size.
- Knows ‘a-prior’ information about signal (i.e. modulation).

CMA

- Blind algorithm – has no ‘a-priori’ knowledge of the signal.
- Tries to equalize signals with a constant modulus/amplitude.
- Want to minimize cost function: dispersion

$$D^P = E(\,|z(n)|^P - R_P)^2$$

- $z(n)$ represents the equalizer output.

CMA

- Steepest descent can be used to minimize dispersion:

$$e_{n+1} = e_n - \mu * \frac{dD^P}{de}\Big|_{e=e_n}$$

- e represents the tap of the equalizer
- µ represents the step size
- Assume:
  - $\frac{dD^P}{de} = 0$
  - $z(n) = a(n)e^{j(x+2\pi dfnT)}$
- $R_p = \frac{E[|a(n)|]^{2p}}{E[|a(n)|]^{p}}$

Channel Models

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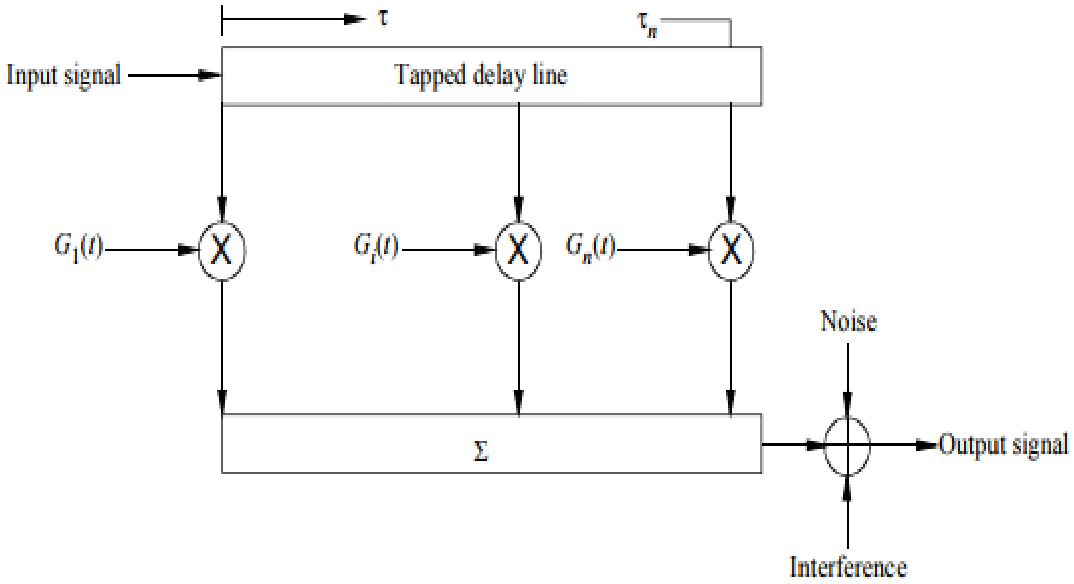
Watterson Model

- Ionospheric reflections modeled using tapped delay line.
- Each tap has a gain function with bi-variate Gaussian power spectrum.
- Simulates signal being corrupted by Rayleigh fading.



[16]

Watterson Model

- Taps used to generate the main taps of the delay line is accomplished using the following equation:

$$h_n(t) = ke^{-(\pi f_j n T_s)^2}$$

- k is a constant used to preserve unity gain
- f_j represents the Doppler spread.
- n represents the tap index.
- T_s represents the symbol period.

Watterson Model

- Model assumes channel is stationary in time and frequency => accurate for small bandwidths.
- Model was implemented to accept delay spread, Doppler spread and number of taps.
- International Telecommunications Union has defined multiple standards indicative of different HF channel conditions.

Channel Condition	Poor	Moderate
Delay Spread (ms)	2	1
Doppler Spread (Hz)	1	0.5

[18]

Proposed Non-linear Channel Model

- During literature review, have not observed a non-linear ionospheric model as verified / heraled as Watterson’s.
- Following equation is our initial attempt to simulate non-linear behavior in the ionosphere:

$$y = x^2 + x + n$$

- y represents signal received by equalizer
- x represents signal corrupted by Watterson model.
- n represents Gaussian noise.

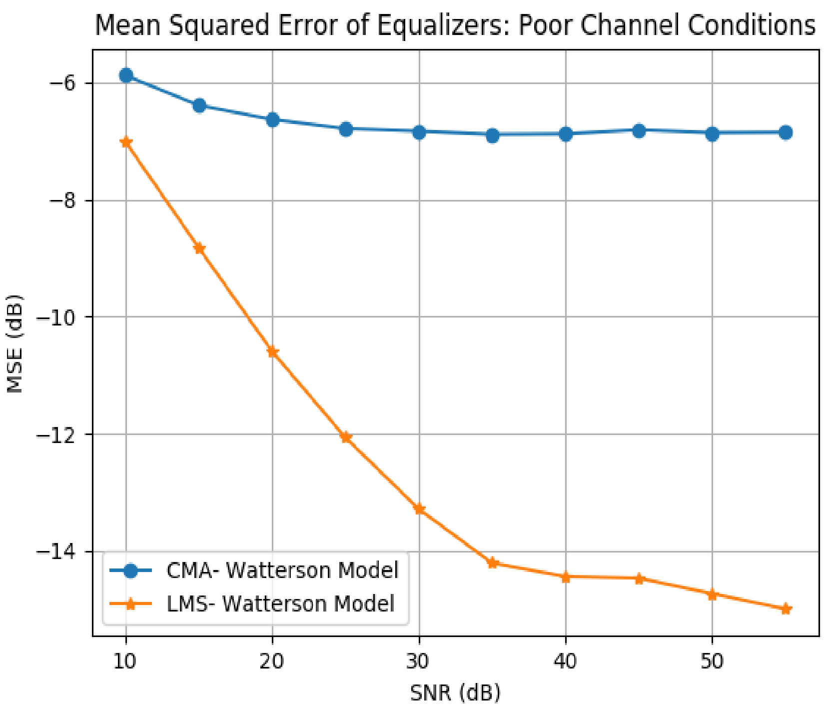
Results

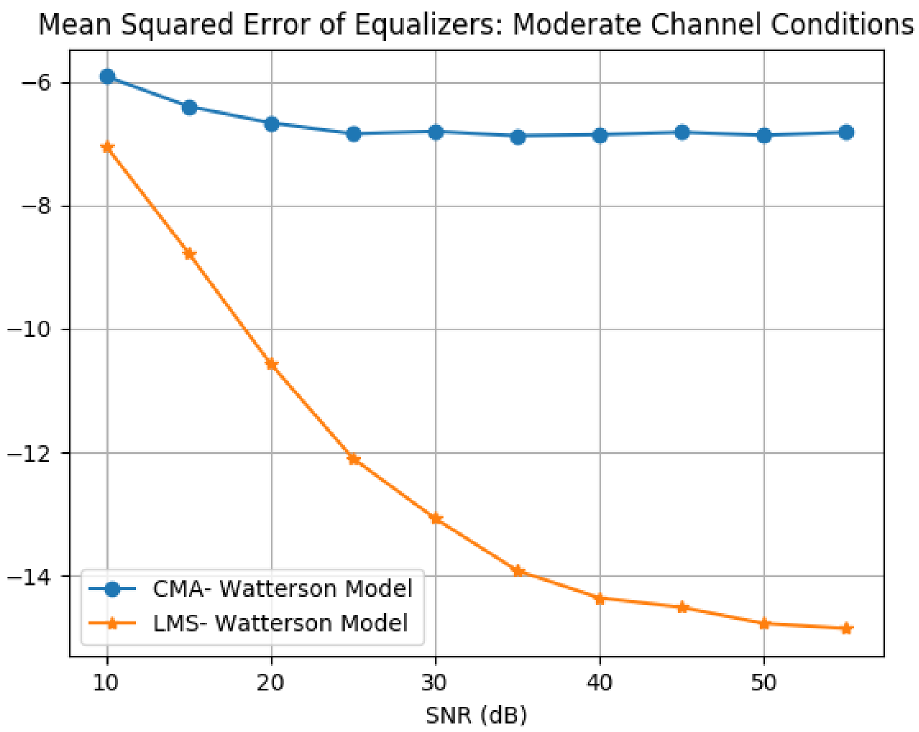
System Architecture

- Implemented using GNU Radio and Python.
- 8-PSK used as primary modulation for all experiments.
- Used both Watterson and proposed non-linear models.
- LMS-DD: Knows the constellation (i.e. 8-PSK).
- CMA: Modulus set to 1.
- Parameters for both equalizers:
  - 4 taps
  - Update gain of 0.01
  - 2 Samples/Symbol

MSE Results

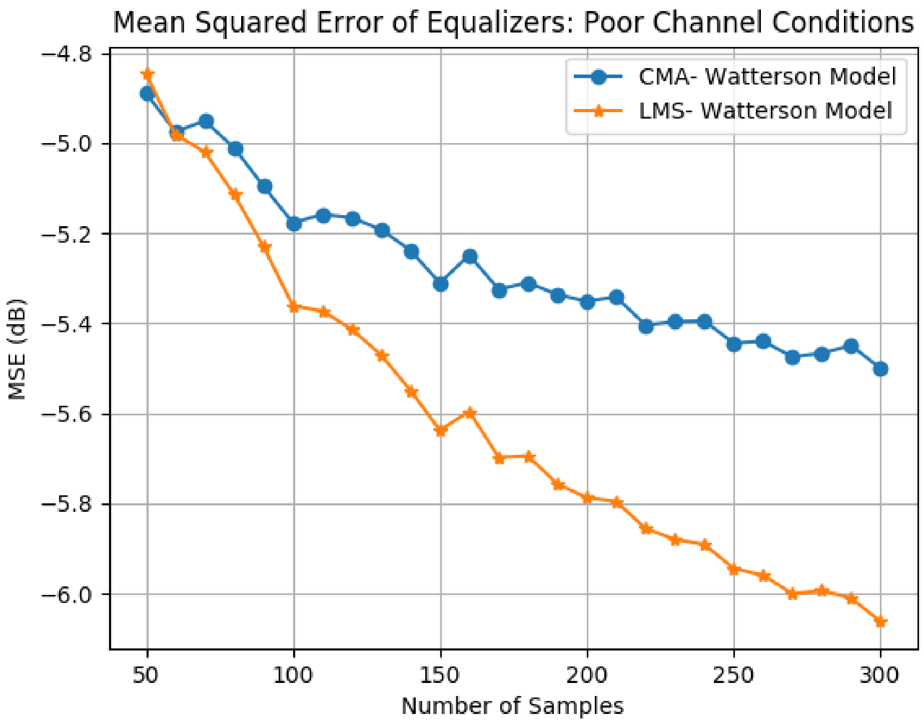
- **Experiment #1: Observe MSE as SNR is varied.**

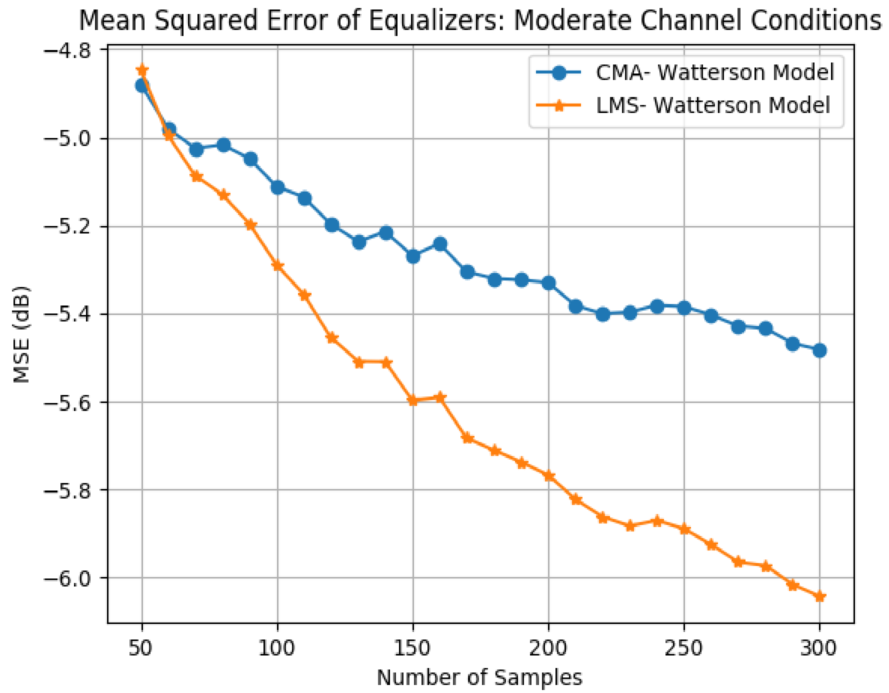




MSE Results

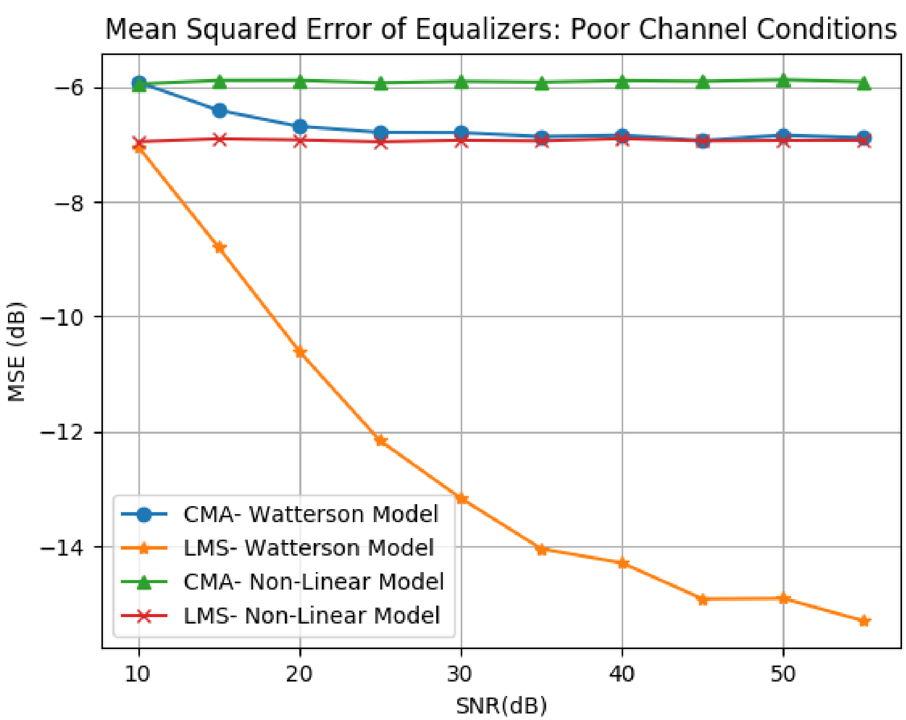
- **Experiment #2: Observe MSE as number of samples is varied at a constant SNR.**

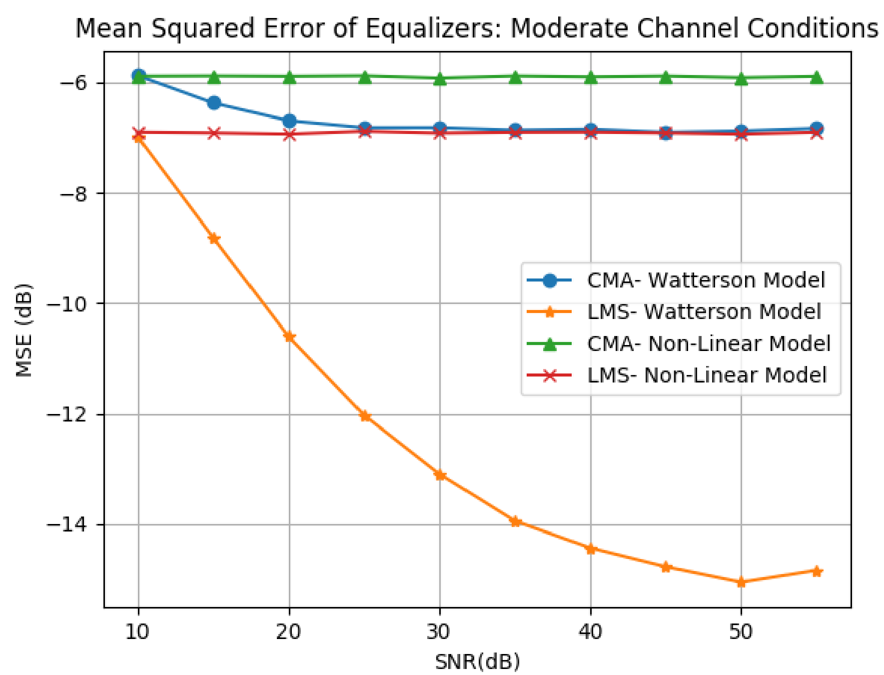




MSE Results

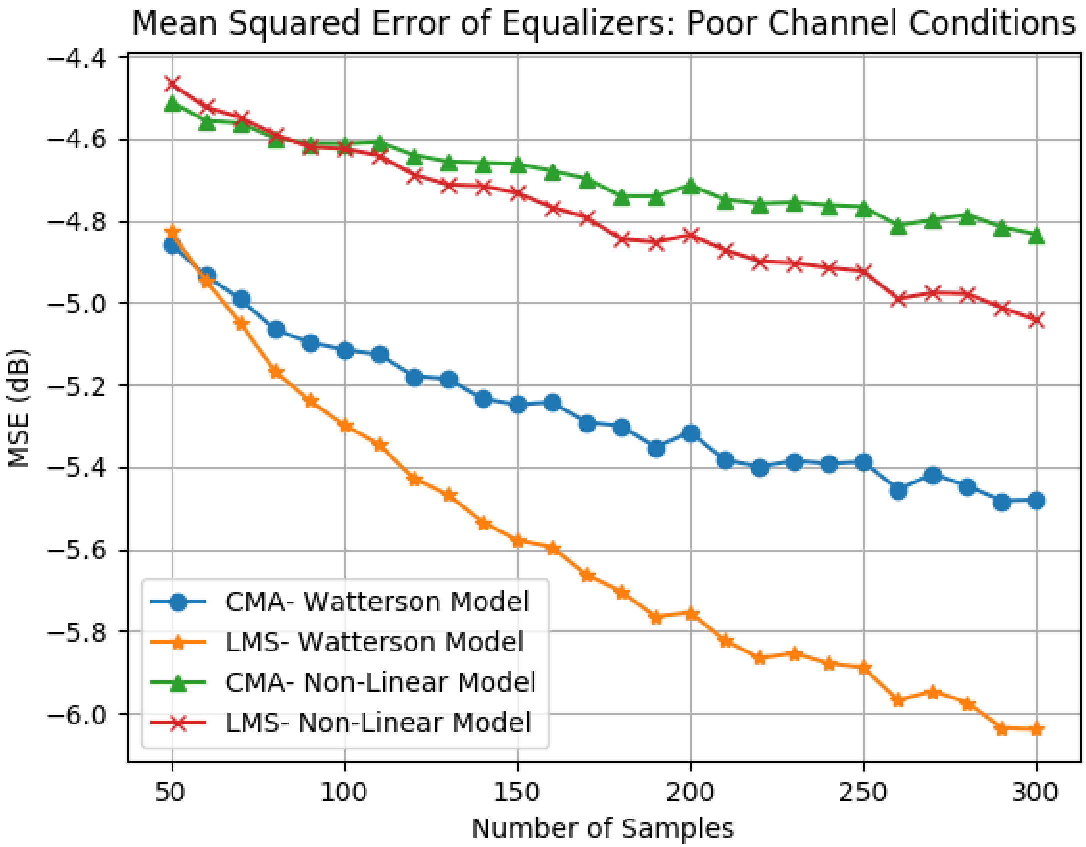
- Repeating Experiment #1 to incorporate non-linear models.





MSE Results

- Repeating Experiment #2 to incorporate non-linear models.



Conclusions / Next Steps

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Conclusion

- LMS-DD equalizer outperformed CMA algorithm in all experiments.
  - LMS-DD has advantage in knowing constellation prior to equalization.
- Non-linear Ionospheric Model provided higher MSEs than Watterson model.
  - LMS-DD still outperformed CMA under these conditions.
  - Increasing SNR/number of samples is not sufficient for resolving non-linear effects.
- Need additional signal processing to be effective in recovering signals from non-linear effects in the HF channel.

Next Steps

- Incorporate more adaptive equalizers:
  - Minimum Mean Square Equalizer (MMSE)
  - Neural Networks
  - Volterra Equalizers
  - Turbo Equalization
- Refine Non-linear Channel model
- Perform over-the air experiments.

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Questions???