SenSIP I/UCRC

SenSIP IAB Meeting

Quantum Linear Prediction for System Identification and Spectral Estimation Applications

Presenter: Aradhita Sharma

Project Lead: Andreas Spanias (PI), ASU

Date: Nov 30, 2023

Project Overview

Motivation:

- Quantum computing has the potential to provide more efficiency and speed in signal processing
- Our prior work with Quantum Fourier transforms published in IEEE ICASSP showed potential
- The research focuses on embracing the quantum era and explore quantum computing for linear prediction to speed up calculations, improve accuracy, and drive innovation.
- Development of a new quantum linear prediction (QLP) algorithm
- System identification, spectral analysis, and analysis-synthesis of the speech signals using QLP.
- Adaptive quantum linear prediction using interpolation.

Project Overview

Quantum Circuits Developed

#1 Quantum Signal Encoding
For encoding speech signals as quantum states.

#2 Quantum Fourier Transform
For exploring DFT application using quantum computing.

#3 Quantum Autocorrelation
For finding autocorrelation using QFTs.

#4 Quantum Linear Prediction
For exploring Linear Prediction applications using quantum computing.

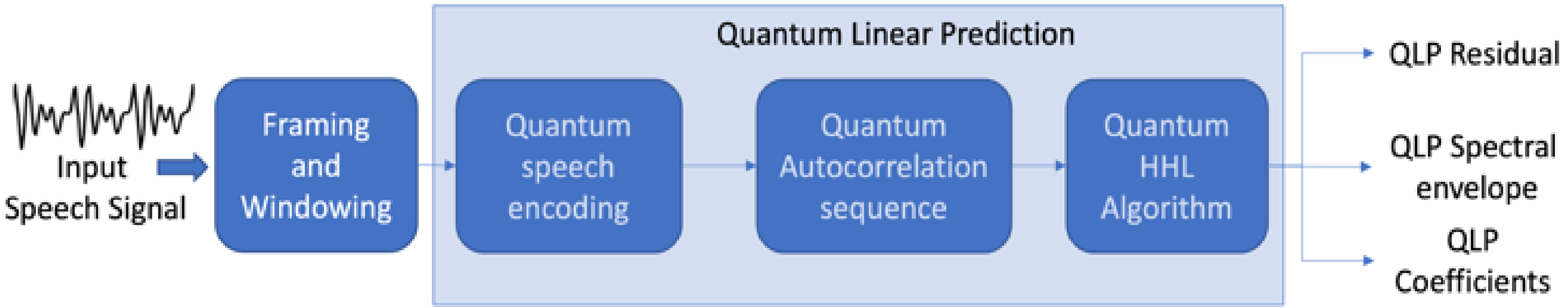
Classical Linear Prediction and Quantum Linear Prediction

Linear prediction (LP) is a common signal-processing technique used to estimate an AR model which reduces the amount of information needed to represent the signal. Statistical method used to model and compress speech signals.

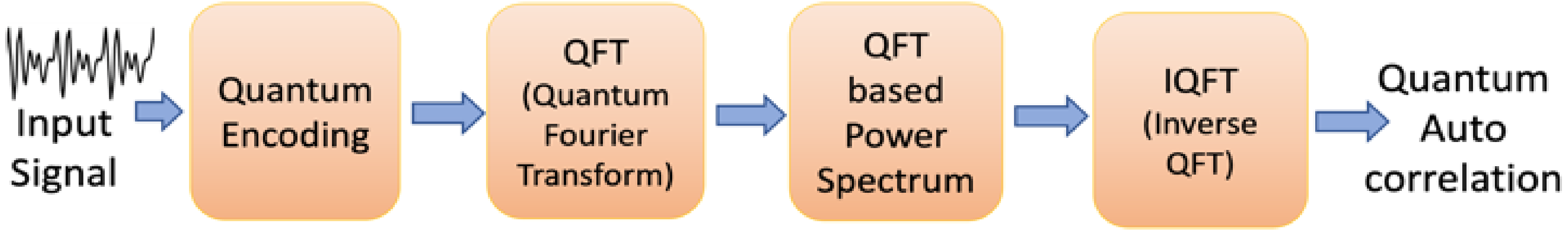
$$s'(n) = \sum_{k=1}^{p} a_k \, . \, s(n-k)$$

Where $s'(n)$ is the predicted value based on previous p values of signal s(n) using the coefficients a_k

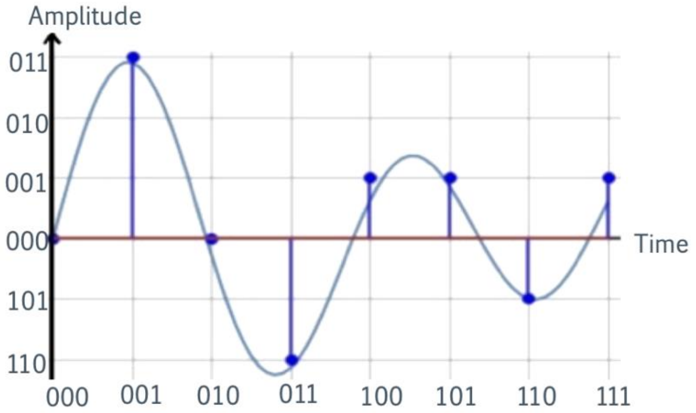
Quantum linear prediction block diagram



Quantum Autocorrelation Computation

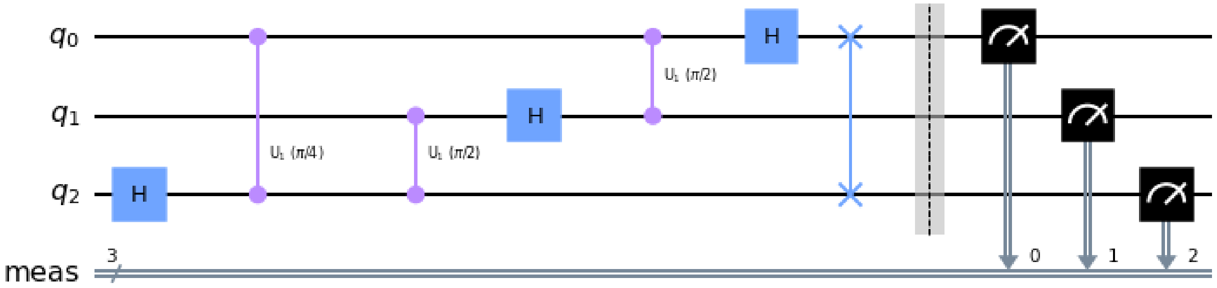


Speech Encoding

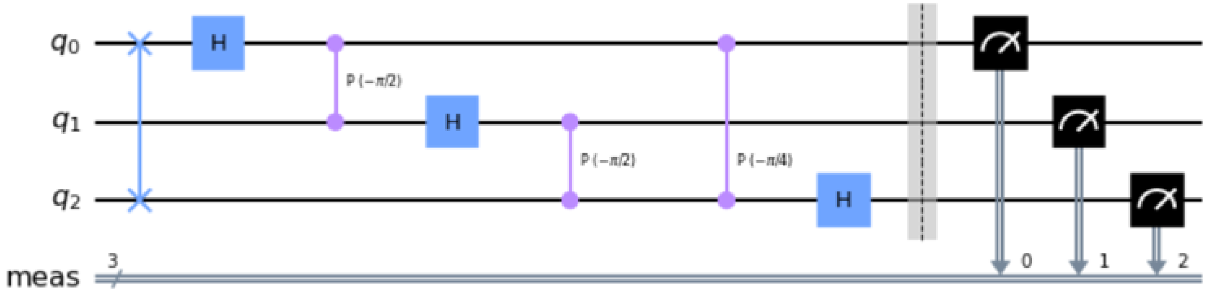


$$|A\rangle = \frac{1}{2\sqrt{2}}\big(|000\rangle\otimes|000\rangle + |011\rangle\otimes|001\rangle + |000\rangle\otimes|010\rangle + |110\rangle\otimes|011\rangle + |001\rangle\otimes|100\rangle + |001\rangle\otimes|101\rangle + |101\rangle\otimes|110\rangle + |001\rangle\otimes|111\rangle\big)$$

QFT Circuit

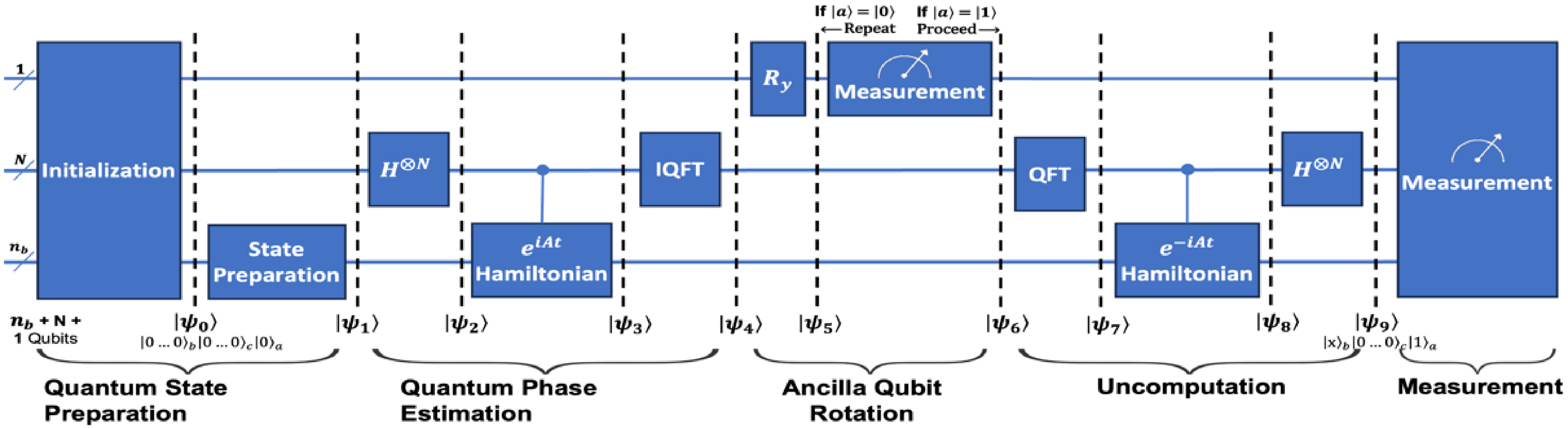


IQFT Circuit

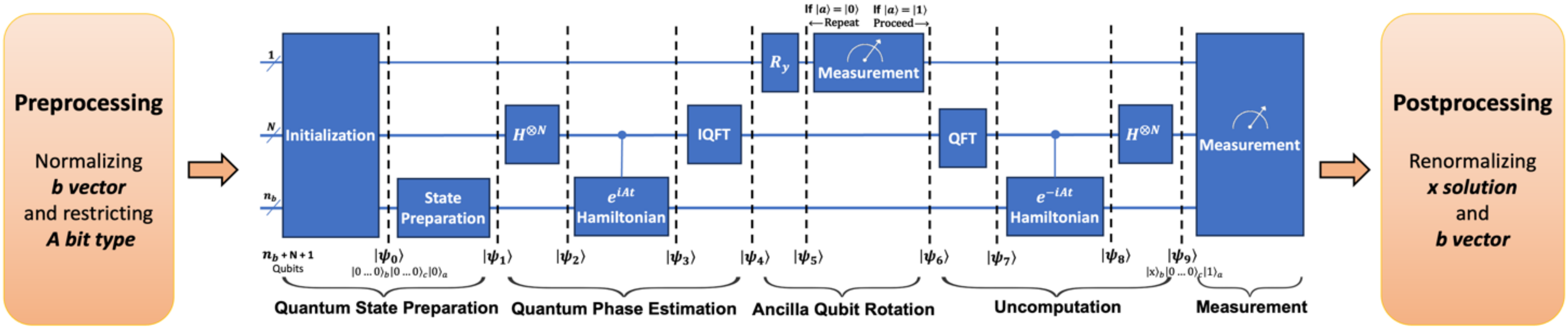


Modified Quantum HHL Algorithm

The Schematic of HHL quantum circuit



The modified HHL quantum circuit with pre and post processing blocks for speech signals



Preliminary Comparative Results

Table 1: MSE comparing classical vs quantum correlations

Qubits	5	6	7	8
MSE	3.45e-32	6.65e-32	1.03e-31	1.33e-31
MSE noise	1.76e-05	2.22e-05	3.37e-05	7.61e-05

→ Increasing trend

Table 3: MSE comparing classical vs quantum solution for 4x4 matrix with different number of qubits.

Qubits	5	6	7	8
MSE	0.000018	0.000161	0.000304	0.000876

→ Increasing trend

Table 2: MSE comparing classical vs quantum HHL solution for different matrix sizes and matrix density.

Matrix Size	Total Qubits	MSE for matrix with different density		
		D = 0.3	D = 0.6	D = 0.9
2x2	5	1.060e-29	1.4757e-7	0.000096
4x4	7	0.0000030	0.000013	0.000249
8x8	9	0.0000448	0.000061	0.004811

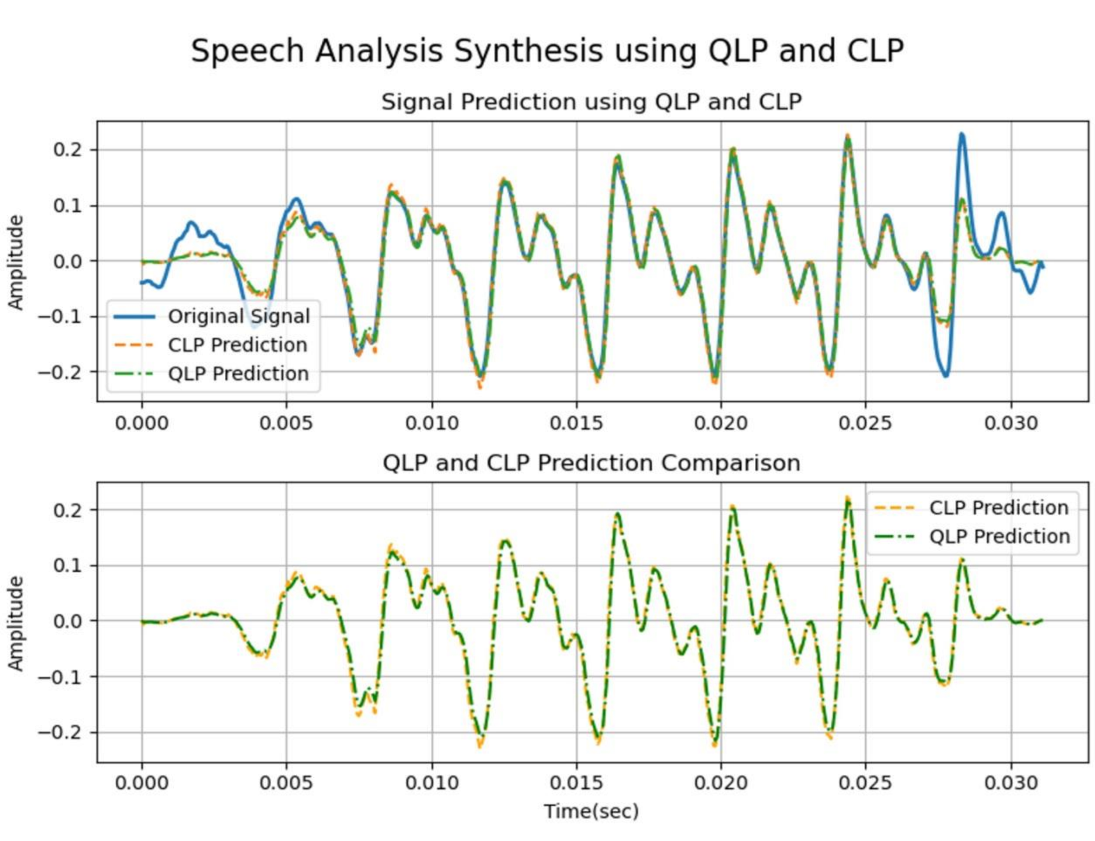
→ Increasing trend ↓

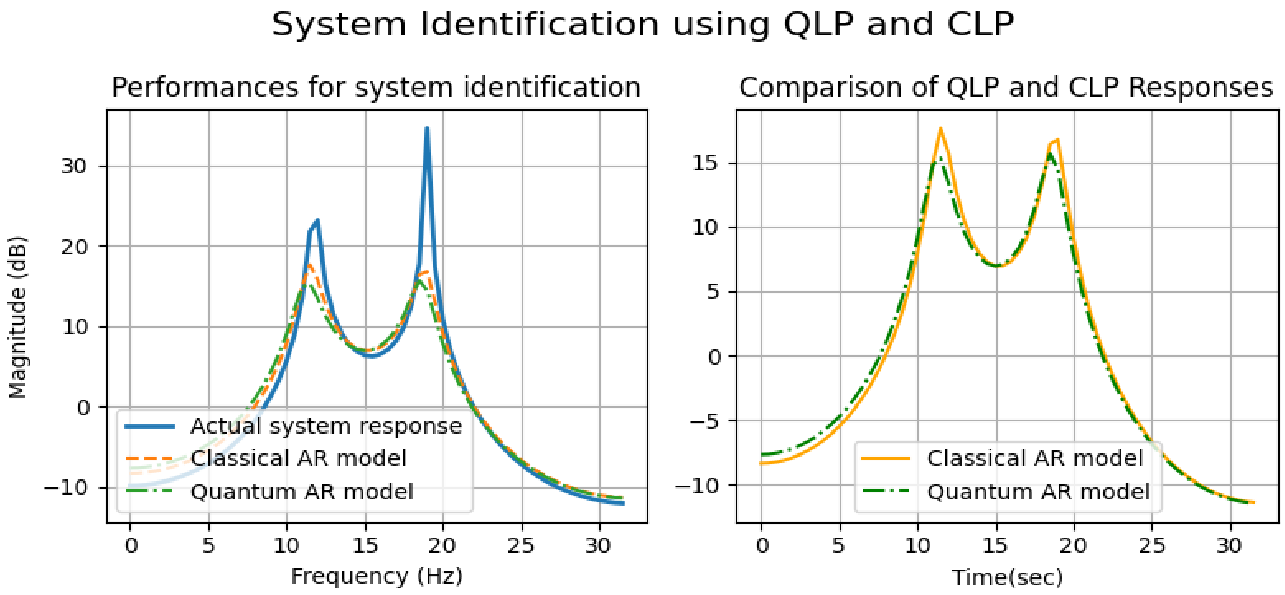
Table 4: MSE for different interpolation weightage ratio for adaptive prediction using QLP.

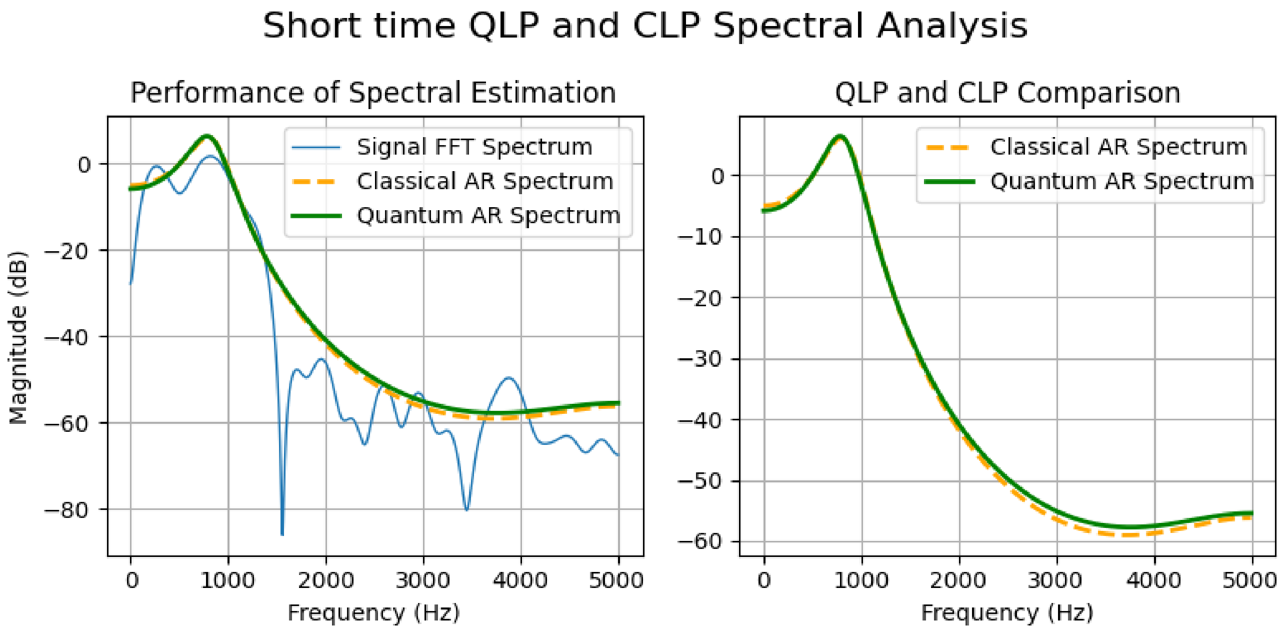
Weight Ratio	% weightage given to the current frame				
	65%	75%	85%	95%	100%
MSE	0.0007526	0.0007521	0.0007520	0.0007522	0.0007524

Optimal: 85% current frame and 25% previous frame interpolation

Preliminary Application Results







Progress to Date and Accomplishments

Task#/Description	Status	Progress and Accomplishments
1. Data Encoding in Quantum states	■ (green)	- Speech data encoded using Amplitude encoding (QRDA).
2. Designing Quantum circuits	■ (green)	- Quantum Fourier transform (QFT) circuit., and Inverse QFT circuit. - Quantum autocorrelation circuit. - Quantum HHL circuit.
3. Speech Processing applications using QFT	■ (green)	- Spectral estimation, Signal analysis-synthesis, Signal compression.
4. Quantum Autocorrelation using QFTs	■ (green)	- Quantum algorithm is developed to perform quantum autocorrelation using QFTs which is faster than convolution.
5. Quantum solution of linear equations using HHL algorithm	■ (green)	- HHL algorithm is developed to work with speech signals, and find out the parameters of autoregressive model for representing speech signals.
6. Quantum linear prediction (QLP)	■ (green)	- Quantum autocorrelation and HHL algorithm combined. - 4^{th} order quantum linear prediction. - Interpolation of QLP coefficients for adaptive prediction.
7. Speech processing applications using QLP	■ (green)	- System identification, Spectral estimation, Speech analysis synthesis.
8. Higher order quantum linear Predictors	■ (yellow)	- To perform computations with larger autocorrelation matrices and build higher order quantum linear predictor for speech processing.
9. Documentation of research and development	■ (yellow)	- Paper publication of quantum linear prediction in Asilomar Conference on Signals Systems and Computers.

■ (green) Task Complete ■ (yellow) Task Partially Complete ■ (red) Task Not Started

Publication of QLP Pending at IEEE Asilomar Conference

QUANTUM LINEAR PREDICTION FOR SYSTEM IDENTIFICATION AND SPECTRAL ESTIMATION APPLICATIONS

ABSTRACT

This paper presents the design and implementation of quantum algorithms and circuits for linear prediction. The intended applications are system identification, spectral estimation, and speech processing using quantum computing. A frequency domain method that uses the quantum Fourier transform is developed to estimate the autocorrelation sequence of the signal and a quantum circuit is used to estimate the autoregressive (AR) parameters. The overall quantum linear prediction circuit is applied to system identification, AR spectral estimation, and speech analysis. Auxiliary hybrid quantum-classical algorithms are used for adapting the AR parameters and extending the order of prediction. The overall study will evaluate performance and complexity in terms of quantum noise effects, qubit precision, and overall computational requirements. Comparisons of quantum versus classical linear prediction will be presented.

Index Terms**—** Quantum linear prediction, quantum Fourier transform, quantum HHL, qubits, quantum autoregressive estimation, system identification, speech analysis.

Conclusions

1. Signal Data encoded as quantum states.
2. QFT based quantum autocorrelation calculation method is developed.
3. Quantum circuits developed for quantum autocorrelation, and quantum HHL algorithm.
4. Quantum linear prediction algorithm is developed for 4^{th} order predictor.
5. Qubit precision effects are analyzed
6. Comparison between quantum and classical implementations is performed.
7. QLP is explored for system identification, spectral estimation, speech analysis, and adaptive speech prediction.

References

[1] A. Spanias, "Speech coding: a tutorial review," *Proc. IEEE*, vol. 82, no. 10, pp. 1541-1582, Oct. 1994.

[2] Makhoul, J, "Linear prediction: A tutorial review." *Proc IEEE 63*, no. 4, pp. 561-580, 1975

[3] Press, W. H., et al. "Correlation and autocorrelation using the FFT." *Numerical recipes in C: The art of scientific computing* (1992).

[4] Nielsen, M.A. & Chuang, I.L., 2011. Quantum Computation and Quantum Information: 10^{th} Anniversary Edition, Cambridge University Press.

[5] G. S. Uehara, A. Spanias and W. Clark, "Quantum Information Processing Algorithms with Emphasis on Machine Learning," *2021 12th IEEE IISA*, Chania Crete, Greece, July 2021.

[6] A. Sharma, G. Uehara, V. Narayanaswamy, L. Miller and A. Spanias, "Signal Analysis-Synthesis Using the Quantum Fourier Transform," *2023 IEEE ICASSP*, Rhodes, Greece, June 2023.

[7] Spanias, A., “Block time and frequency domain modified covariance algorithms for spectral analysis.” *IEEE Trans. signal processing*, *41*(11), 3138-3152, 1993.

[8] Harrow, Aram W., Avinatan Hassidim, and Seth Lloyd. "Quantum algorithm for linear systems of equations." *Physical review letters* 103.15 (2009).