Introducing Quantum Computing in a Sophomore Signals and Systems Course

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***Abstract*— This Innovative Practice Work in Progress Paper describes the development and assessment of a web-based simulation lab exercise introducing basic quantum computing concepts in a sophomore signals and systems course. Specifically, students make the connection between quantum computing and signals and systems theory through a comparative study of using Quantum Fourier Transforms and Fast Fourier Transforms for a speech analysis-synthesis application. In addition, quantum noise models are introduced and simulated to show their effect on computation performance. Statistics from pre/post quizzes show that there is significant knowledge improvement by completing the lab exercise.**

***Keywords*— Undergraduate, Quantum Computing, Simulation, Signals and Systems, Quantum Fourier Transforms, Qubit, Quantum Noise.**

I. Introduction

With the significant development in the past decade in the field of Quantum Information Science and Technology (QIST), a new quantum industry has emerged towards the development of quantum-enabled products and applications [1-2]. To prepare a talent pool with appropriate knowledge and skills to work in this emerging market, many educational efforts have been put into place to help train a quantum-aware and quantum-proficient workforce. Efforts range from K-12 programs, enhanced undergraduate degree programs, workforce development, and newly developed master's level degree programs [3-4].

This paper takes a different approach. A web-based simulation lab exercise is developed to introduce quantum computing to students in a signals and systems course. Signals and Systems I is a sophomore level required course in the electrical engineering online bachelor degree curriculum. It covers basic signals and systems concepts such as signal transformation, linear time-invariant systems, Fourier series, Fourier transforms, Laplace and Z transforms. Besides teaching theoretical concepts, MATLAB labs were incorporated to help students connect theory with practical applications [5].

Specifically, this newly developed web-based simulation lab exercise helps students make the connection between quantum computing and signals and systems theory through a comparative study of using Quantum Fourier Transforms and Fast Fourier Transforms for a speech analysis-synthesis application. In addition, quantum noise models are introduced and simulated to show their effect on computational performance. Due to its intuitive interface, students require no prior software and hardware training in quantum computing.

This paper discusses the development of the web-based quantum computing simulation interface, and the associated lab exercise introducing students to Quantum Fourier Transforms and quantum noise. The impact of this addition is evaluated through pre/post quizzes. The rest of the paper is organized as follows. First, educational programs on Quantum Information Science and Technology (QIST) is briefly reviewed in the background section. The development of the web-based simulation lab exercise on quantum computing is described next, followed by the assessment, results, and conclusion.

II. Background

To help develop the quantum workforce, a growing number of quantum education efforts emerge at all academic levels.

Games, activities, and interactive tools geared toward K-12 audiences are developed in [6]. Experiences in teaching quantum computing to high school students are presented in [7]. A roadmap is provided in [8] on how to build a quantum engineering undergraduate program. The history, development, and first-year operation of an undergraduate degree in quantum engineering are discussed in [9]. The development of new undergraduate courses to teach students quantum computing through programming is discussed in [10] using Microsoft Q# [11] and in [12] using IBM's Qiskit framework [13]. A virtual program for STEM field undergraduate students in quantum machine learning (QML) is described in [14] which explored quantum computing for image processing [15], voice recognition [16], photovoltaic topology optimization [17] and homomorphic encryption [18]. Several quantum computing and quantum information science master's degree programs are listed in [4]. How a quantum computing and information specialization is created in an electrical engineering master's degree program is described in [19].

Different from the efforts mentioned above, this paper describes a new approach of training engineering students to become quantum-aware through integrating an easy-to-use web simulation lab exercise into an existing electrical engineering core course. The basic quantum computing concepts are introduced in the context of a classical signal analysis synthesis application.

III. Implementation

The Quantum Fourier Transform (QFT) algorithm is a fundamental algorithm in quantum computing that is used in a variety of applications and is analogous to the discrete Fourier transform. Therefore, this algorithm is used for implementing signal analysis synthesis [20] using quantum computing. However, implementing the QFT algorithm using Qiskit [21] can be challenging for beginners due to limited time to introduce in an undergraduate class. Therefore, quantum computing simulation is introduced through the J-DSP platform [22-23], which provides an intuitive way to describe the QFT algorithm using a graphical interface. J-DSP is an interactive, user-friendly simulation software, which has been used by many universities to provide online laboratories of digital signal processing (DSP) to undergraduates. This block diagram-oriented simulation environment enables students to execute DSP simulations effortlessly by connecting and configuring different functional blocks from any computer with internet connection.

A. Quantum Computing Blocks in J-DSP

For the quantum computing simulation, quantum computing blocks for the J-DSP are developed. The theory and software details of developing these quantum computing blocks is described in [24] and the quantum signal analysis synthesis implementation is disclosed in [25]. Students can simply drag and drop these blocks and connect them together to perform the QFT-based signal analysis synthesis. The blocks are shown in Fig. 1 and are described below.

1) QFT and IQFT Blocks: QFT and IQFT blocks are developed to represent the Quantum Fourier Transform and its inverse as mentioned in equation (1).

$$QFT|n\rangle \rightarrow \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} e^{\frac{2\pi ikn}{N}}|k\rangle, \quad IQFT|k\rangle \rightarrow \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} e^{-\frac{2\pi ikn}{N}}|n\rangle \quad (1)$$

where $|n\rangle$ is the frequency representation of the $|k\rangle$ time domain signal, and $N = 2^m$ where m is the number of qubits [26]. QFT and IQFT blocks are implemented for different number of qubits such that students can simply select the number of qubits *(m)*.

2) Normalize Block: A normalized block is developed that normalizes the measurement results of QFTs and IQFTs to be in the desired range. By using this block, students can easily interpret the measurement results of QFTs and IQFTs and compare them to the classical FFTs and IFFTs.

3) Quantum Noise Block: To model the effects of quantum noise, a quantum noise block is developed, which represents the effects of quantum noise, including measurement errors, amplitude damping errors, and phase damping errors [25]. Students can explore how quantum noise affects the output of the algorithm for different number of qubits.

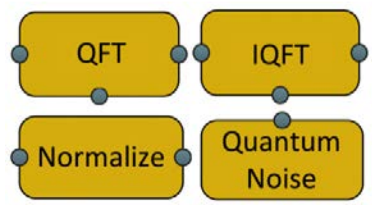

Fig. 1. Quantum Computing J-DSP Blocks.

B. Quantum Exercise of QFT-based Signal Analysis Synthesis

To learn about quantum computing applications, an exercise is developed using QFT-based signal analysis synthesis, where students perform this exercise and analyze the performance for different numbers of qubits, quantum noise, and different numbers of selected frequency components for synthesis. Students also perform the classical FFT-based signal analysis synthesis and compare the QFT and DFT performances.

The block diagram of the exercise is shown in Fig. 2. Input speech signal can be generated from a signal generator block (Sig Gen (L)), which is connected to the FFT block to obtain frequency representation of the signal. The FFT block is then connected to the Peak Picking block which is used to select first (L) or largest (L) frequency components, which is connected to the IFFT block to reconstruct the signal back and calculate the SNR of the FFT reconstructed signal. Similarly, for QFT-based signal analysis synthesis, the Sig Gen block is connected to the QFT block with a Quantum Noise block attached, which performs the QFT algorithm in the presence of quantum noise. The Peak Picking block selects either the first (L) or largest (L) frequency components obtained by the QFT algorithm to analyze Parseval's theorem. The IQFT block is used to convert these selected QFT components back to the reconstructed signal. The output of the QFT and the IQFT block is attached to the Normalize block to be comparable to the classical results.

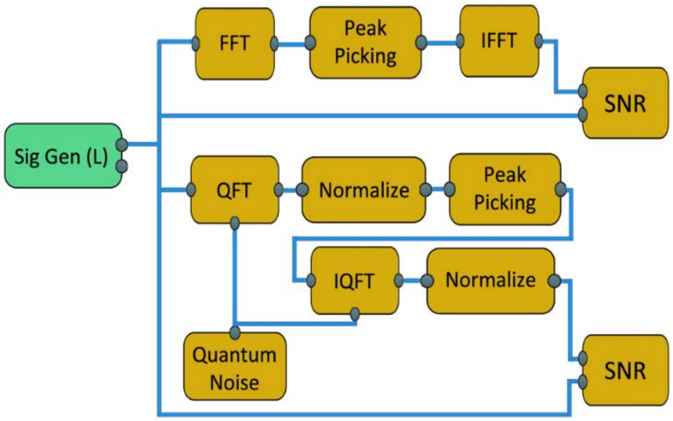

Fig. 2. DFT and QFT-based Signal Analysis Synthesis Block Diagram.

IV. Assessment and Results

The quantum computing web-based J-DSP simulation lab exercise is incorporated in the signals and systems course and was piloted in the spring semester of 2023. It is presented to students after covering the topic of discrete time Fourier transform. Before performing the lab exercise, students are asked to complete a pre-quiz to assess their prior knowledge of quantum computing. The quiz assessment includes the basic quantum computing questions, and the comparisons of DFT and QFT-based simulation questions. Students then read a tutorial on the introduction of quantum computing, Quantum Fourier Transforms, quantum noise and a tutorial on developed DFT and QFT-based signal analysis synthesis lab exercise. After the tutorials, students perform the lab exercise using the web-based J-DSP simulation interface. After completing the lab exercise, students repeat the same quiz again for the post-quiz assessment. In this study, twenty students completed both the pre- and post-quizzes.

The abbreviated pre/post quiz questions are shown in Table I, where Q1-Q3 are the basics of quantum computing and quantum noise, and Q4-Q13 are based on QFT and the comparisons of QFT and DFT. Most quiz questions are multiple-choice with a few true/false questions.

TABLE I. Pre- and Post- Quiz Questions

Number	Questions
1	Quantum computing is anticipated to be much faster than classical computing. Anticipated speeds are:
2	What is the numerical building block of quantum computing?
3	Which of these noise types are typically observed in quantum computing?
4	What is the range of the output value of a quantum Fourier transform (QFT) circuit?
5	What is the computational complexity of the QFT algorithm, where N = 2^n, and "n" is the number of qubits?
6	Does the QFT accuracy improve as one increases considerably the number of qubits for computation considering quantum noise effects?
7	What is the normalization factor for obtaining the IQFT coefficients?
8	Which L QFT components selection results in a greater SNR compression process for signal analysis-synthesis (L<N)?
9	What happens to the SNR value when one increases the number (L) of selected QFT components in the QFT compression process?
10	The SNR value for QFT signal analysis synthesis in presence of quantum noise is less than that of the SNR obtained for the DFT analysis-synthesis process when the number of Fourier components and size of the transform are the same in both cases. True or False?
11	In the QFT compression process under ideal conditions (no quantum noise) the SNR will generally increase when the number of components L increases because:
12	The SNR values for the DFT and QFT Simulations are identical. True or False?
13	The QFT compression scheme can be extended to 2-D images. True or False?

The number of students with correct answers for the thirteen questions in Table I is summarized in Fig. 3. This gives us a visual comparison of the correct responses for each question for the pre (blue bars) and post (red bars) quiz.

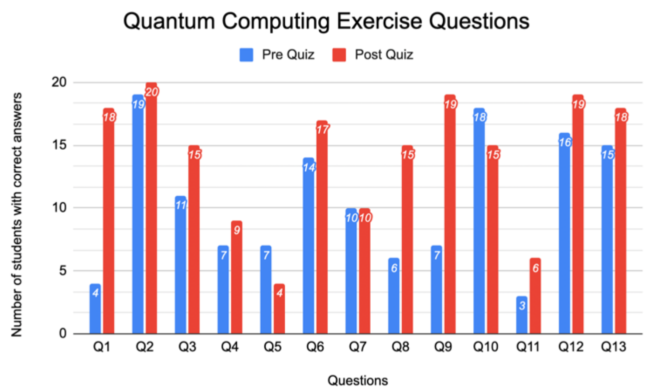

Fig. 3. Evaluation Assessment Results for the QFT simulation exercise.

From Fig. 3, it is observed that more students answered correctly in the post-quiz compared to the pre-quiz, with the only exceptions of Q5 and Q10. We believe that the wording of these two questions might have caused some confusion.

The biggest improvement is from Q1, i.e., more students have a better awareness of the speed gain of quantum computers compared to classical computers after completing the exercise. Students also have a better understanding of Parseval's theorem and related compression algorithm as seen from Q8 and Q9.

A paired two-sample t-test is performed on the mean number of correctly answered question on pre- and post-quiz out of the thirteen questions. Participants scored significantly higher on the post-test (with a mean of 8.55 and a standard deviation of 2.04), than on the pre-test (with a mean of 6.45 and a standard deviation of 1.57) after completing the lab exercise. The P-value is less than 0.001.

Besides testing students' knowledge of quantum computing, there are a few more questions used in the quiz to collect feedback regarding the lab exercise and the web-based J-DSP simulation interface. The results from the three true/false questions (Q14-Q16) are shown in Fig. 4. Q14 shows that at least nine out of twenty students have no knowledge of IBM Qiskit simulation. Q15 and Q16 show that more than half of students feel that the lab exercise helps them understand QFT-based compression. More than two-thirds of students have a better understanding of the effects of quantum noise after the exercise.

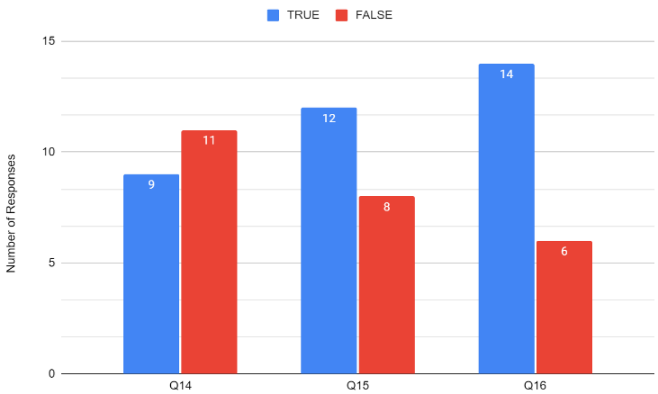

Fig. 4. Results for the feedback questions: Q14: J-DSP quantum functions behave exactly as an IBM Qiskit simulation; Q15: J-DSP helped with understanding at an introductory level QFT-based compression; Q16: J-DSP QFT functions helped me understand at an introductory level the effects of quantum noise.

Figures 5 and 6 show that most students think the web-based J-DSP simulation lab exercise can be deployed in an early-level signals and systems class or other undergraduate digital signal processing (DSP) class, however, multiple introductory lectures on quantum computing and Quantum Fourier Transforms are needed.

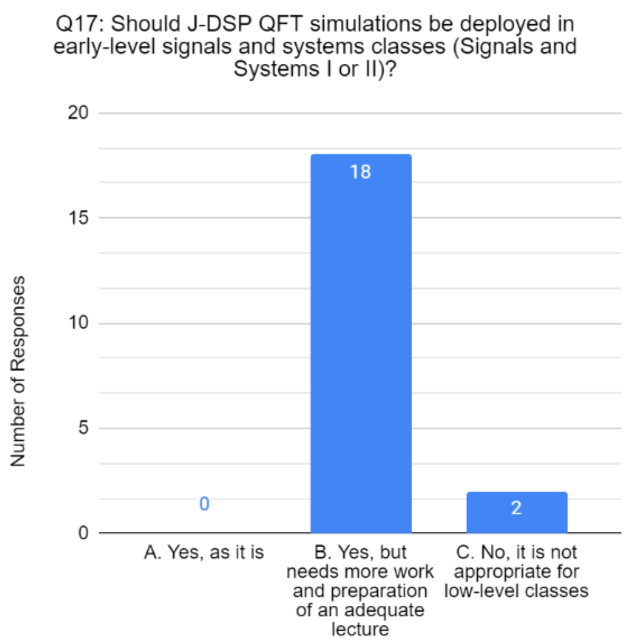

Fig. 5. Result for the feedback question: Q17: Should J-DSP QFT simulations be deployed in early-level signals and systems classes (Signals and Systems I or II)?

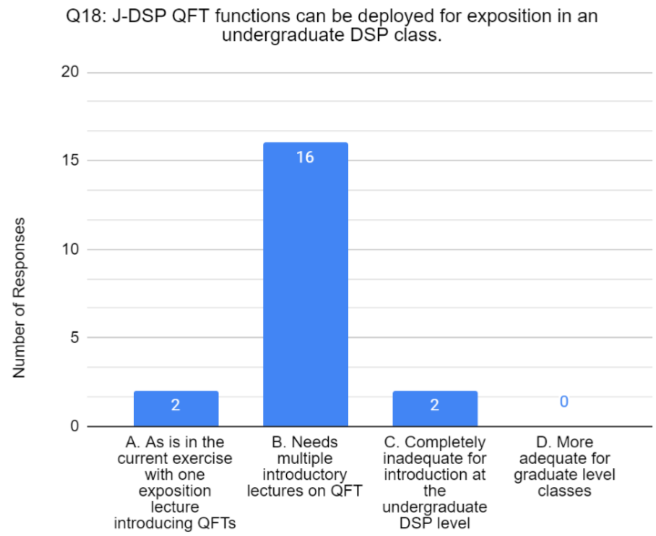

Fig. 6. Result for the feedback question: Q18: J-DSP QFT functions can be deployed for exposition in an undergraduate DSP class.

Additional feedback from students regarding the occasional crashes and sometimes slow execution of the simulation interface indicates that further improvement of the software is needed.

V. Conclusion

A web-based J-DSP simulation lab exercise is incorporated in a sophomore signals and systems course to introduce students to the basic concepts of quantum computing. Statistics from pre/post quizzes show that there is significant knowledge gained by completing the lab exercise. Most students think the lab exercise can be deployed in an undergraduate signals and systems or digital signal processing class, however, multiple introductory lectures on the topic are needed. Further improvement on the software is also desired. Additional evaluations will be performed in the Fall of 2023. Future work will introduce more quantum blocks and address image processing problems [27] using quantum computing.

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