CHAPTER 1
INTRODUCTION

1.1 Background

Quantum information is related to the use of quantum mechanics concepts to perform information processing and transmission of information [1, 2]. The sixth telecommunication generation (6G) research on Quantum Information Processing (QIP) has numerous applications and has become the key parameter for future communications, including quantum key distribution (QKD), quantum teleportation, and quantum computing. Quantum processor [3] based on superconductor can perform computations of dimension $2^{53} \approx 9 \times 10^{15}$. This is beyond the fastest classical-quantum that makes quantum computing become the key to future communications. On the other hand, quantum computing's major problem is decoherence. Decoherence makes a superposition states blur and also introduces errors. That indicates the quantum register should isolate from the environment so that only a few random occurs. One of the solutions is quantum error correction codes (QECC).

Quantum bit (qubit) are not allowed to be cloned like classical codes, but can be modified with entanglement. In quantum terms, there is no mapping like Quadrature Amplitude Modulation (QAM) and Phase Shift Keying (PSK). For encoded messages in quantum, QECC use a logical operator which is not in the classical codes. Another turning down point could be the fact that despite the intensive development of quantum algorithms, the number of available quantum algorithms is still small compared to classical algorithms.

The ideal environment for a global quantum internet is independent qubits teleportation over a free-space link between a satellite and a ground station. Based on the experiment of 143 kilometers between Tenerife and La Palma [4], quantum internet is mixed by quantum and classical communications with the combination of a frequency uncorrelated polarization-entangled photon, ultra-low noise single-photon detectors, and entanglement assisted clock synchronization techniques. The second experiment [5] is quantum teleportation across the tunnel that is installed in a public system located in a tunnel underneath the River Danube implemented by using an 800 meters long optical fiber. This experiment proved that the quantum internet can be implemented by mixing quantum technology with current technology.

De Broglie in 1924 declared that every element of matter like atom, electron, and photon has both particle-like behavior and wave-like behavior. Schrödinger in 1926 referred to De Broglie, to formulate the equation to make a closed form of quantum mechanical system as wave mechanics. Heisenberg in 1925 formulated the alternative of quantum theory called matrix mechanics. This theory uses matrices and linear algebra.

Paul Dirac published a textbook in 1930 that unifies the Schrödinger and Heisenberg formula as being equivalent. Heisenberg pictures carry time evolution exclusively by the physically observable. This logical expression becomes particularly useful when describing the quantum information encoding process. Heisenberg's equation on the measurement uncertainty helps us to make possible simultaneous measurements if the stabilizers generator is a commute. This is one of the useful theories in quantum state measurement used for error corrections.

Several studies about QECC including the perfect 5-qubit codes [6], where 5 qubits are the minimum required number of encoded bits that can make corrections on all possibilities against a single error using four stabilizers. This method is rarely used due to the complexity of the calculation process. Chalder-bank Shor Steane (CSS) codes [7] can make corrections to all possible single error by copying the Z stabilizer against the stabilizer X, but CSS codes require more stabilizers to detect one error. Therefore, CSS codes are more wasteful than the perfect 5-qubit codes. Shor 9-qubit codes [8] can detect all combinations against one error as well using calculations that are more simple in encoder circuit complexity than the perfect 5-qubit codes, but more wasteful than CSS codes because it requires 9 stabilizers just to detect a single error.

This thesis needs to find the correct stabilizers for the receiver and the $\bar{X}$ and $\bar{Z}$ for the transmitter to be capable of detecting and correcting the error. In the first step, this thesis generates the stabilizers from the parity check matrix H. The value of modulo 2 of Symplectic Inner Product (SIP) should be zero to confirm that all stabilizers are commutative. In the second step, this thesis generates the $\bar{X}$ and $\bar{Z}$. The requirement of reduced-row echelon form (RREF) of parity check matrix should be an integer or close to an integer. In the third step, this thesis generates the syndrome to detect and correct the errors.

This thesis studies the encoding and decoding construction of QECC then applies the concept to the accumulator for lower quantum syndrome measurement complexity while keeping good performance. This thesis uses accumulate codes that have a repeating pattern and these codes can help error correction reach mutual information one on classical codes. Hopefully, this thesis has the same impact on QECC in the future. These codes have a high rate because can correct two qubits of information.

These codes are efficient because refer to Hamming bound [9]. This thesis achieves the minimum blocklength to correct $k = 2$ and has high error correction capability because the distance of quantum $[[12,2,4]]$ accumulate codes is 4. Therefore the proposed method is expected to become one of the perfect quantum codes and work well to correct all possibilities of two simultaneous errors of X, Z, Y using a short blocklength of 12 qubits.

1.2 Problem Identification

The current perfect quantum $[[5,1,3]]$ codes that capable of correcting one qubit are still complex. The complexity in design causes complexity in hardware realization, which will delaying the applications of quantum communications and fault-tolerant quantum computing to the market and business. The complex circuit indicates that the complex encoding to prepare the codespace (or codewords in classical coding) represented by the logical operators $\bar{\mathbf{X}}$ or $\bar{\mathbf{Z}}$.

Furthermore, the current quantum codes are in general designed for information $k = 1$ causing a low bit rate and small throughput of quantum communications. Higher transmission efficiency ”indicated by $k = 2$” is needed in the future for better communications.

1.3 Objective and Contributions

This thesis aims to design QECC with a high coding rate (have more than one qubit information). This thesis also aims to design decoders construction of quantum accumulate codes that can correct more than one qubit error. The overall contributions are summarized as follows:

1. This thesis proposes quantum accumulate codes, which is efficient to detect and correcting error.
2. This thesis evaluates possible errors and how to correct them.
3. This thesis provides an analysis of performance, evaluated on QWER depolarizing channel.

1.4 Scope of Research

The scope of research in this thesis is limited to:

1. The blocklength codes are kept short, i.e., 12 qubits. A further extension to larger blocklength is expected to be straightforward following the suggestion in [10].
2. This thesis focuses on $[[12,2,4]]$ codes with 12 qubits and 10 stabilizers generators derived from classical accumulator codes.
3. This thesis uses syndrome extraction as in [10] rather than developing state correction as used in $[[9,1,3]]$ Shor codes.
4. The performances of all codes are evaluated in terms of qubit error rate (QWER).
5. A series of computer simulations are conducted.

1.5 Research Methodology

This thesis is divided into 3 work packages (WP) to produce high-quality results.

- WP1: Study on literature
  Studies on basic theories related to Accumulate codes. Literature studies help explain basic theories to help the encoder and decoder model, error correction systems, the proposed systems, and the results of the analysis.
- WP2: Design Quantum Error Correction codes with accumulate codes
  This thesis does QECC scheme design based on accumulate codes to obtain a logic gate scheme with lower complexity.
- WP3: Prove the Quantum Word Error Rate (QWER) performances
  This thesis evaluates the performance of quantum accumulate codes correction against QWER.

1.6 Organization of the Thesis

The rest of this thesis is organized as follows:

- **CHAPTER 2: BASIC CONCEPT**
  This chapter describes the basic theory of the proposed quantum accumulate codes and related research.
- **CHAPTER 3: THE PROPOSED QUANTUM ACCUMULATE CODES**
  This chapter describes the considered quantum accumulate codes system model and the coding design.

- **CHAPTER 4: PERFORMANCE EVALUATIONS**
  This chapter describes performance evaluations of the proposed quantum accumulate codes system model and coding design.
- **CHAPTER 5: CONCLUSION**
  This chapter describes the conclusion of the research