

My Report

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Abstract

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1. INTRODUCTION

Modern cryptography is a field that is largely concerned with the development of secure algorithms for symmetric or asymmetric encryption, either relying of complex shuffling procedures in the case of the former, or on complex mathematical problems in the latter case. Both types of encryption schemes come with certain drawbacks that make them more or less viable in different scenarios. For instance, asymmetric encryption by its often mathematical nature can be quite computationally intensive, especially on a larger scale. On the other hand, symmetric encryption relies on the distribution of a shared key that needs to stay secure from prying eyes. For this reason, the two types of encryption are most often used in conjunction with one another, where asymmetric cryptography is used to distribute a private key that is then later used in a symmetric encryption scheme. Such is the case with TLS, which is used in virtually all communication on the Internet today.

However, with the advent of quantum computers, the asymmetric encryption schemes used today are threatened as the new computational powers captured by quantum mechanics allows adversaries to tackle the mathematical underpinnings of most such schemes. In this work, we investigate an alternative approach to cryptography, or more specifically to the key distribution phase of secure communication, that also utilize the powerful properties of quantum computation. Through quantum key distribution, it is possible to obtain methods for distributing private keys without relying on classical asymmetric encryption schemes.

§ 1.1. Background. The goal of Quantum Key Distribution (QKD) is to securely share keys between multiple parties using properties of quantum mechanics. The key property utilized here is the fact that an entangled quantum state shared between two parties, the definition of which is given in Section 2.2, cannot be eavesdropped upon without permanently disturbing the system in a detectable way. So in theory, QKD promises to provide a perfectly secure way to distribute keys between multiple parties thereby solving the inherent issue of using symmetric encryption schemes such as the provably secure one-time pad.

The first protocol for QKD, known as BB84, was introduced by Bennet and Brassard in [1] and did not rely on quantum entanglement. The idea of using entanglement to prevent eavesdropping and to obtain a perfectly random string as a shared key was suggested by Artur Ekert in [6], and laid the ground for the field of QKD to this day. The primary developments within the field since Ekert's scheme mainly concern the specification of the devices involved in the protocols.

The security proofs of the traditional QKD protocols did not take into account

attacks on the infrastructure used in the practical implementation, such as the quantum devices used in the procedures. This was soon discovered to be a significant flaw in these protocols as it left them vulnerable to side-channel attacks, for instance [2]. In general, assuming the security of the devices as characterized by the protocols was found to be a strong assumption which left the suggested QKD schemes fundamentally vulnerable to novel attacks targeting flaws in the device implementation.

The solution to this issue was suggested in [8] which introduced the concept of *device-independent* QKD, or diQKD. In this new paradigm, no specifics are given as to the implementation of the quantum devices involved. Rather, the security of the devices is proven based on their behavior in terms of their input and output. If, during the execution of the protocol, the devices are found to deviate from their expected behavior, the protocol is terminated as it could indicate an ongoing attack. In modern diQKD protocols, so-called *Bell tests* are often used to perform this check due to its correlation properties as we will explore in Section 2.3. The major drawback to diQKD is that the implementation of such protocols often is less clear than in their device-dependent counterparts as it requires the implementation of so-called loophole-free Bell tests, as we will discuss later.

There are also a few different approaches to generating the key and detecting eavesdroppers, by using different aspects of quantum mechanics. Some, like Ekert's protocol [6], rely on entanglement to exchange the key through the perfectly correlated quantum particles, while others, such as BB84, rely on Heisenberg's uncertainty principle to guarantee that an eavesdropper will be detected by the involved parties. For a comprehensive and recent review of the existing techniques, challenges, and protocols within the area of QKD the interested reader may refer to [7].

Since this thesis will focus on the implementation and simulation of QKD protocols we here also include a note on quantum programming and techniques for simulation. Much like for classical computers, to execute operations on quantum processors, a quantum instruction set is utilized. Today, there is a large number of offerings in this area from a number of large corporations and organizations. We here rely on the software development kit Qiskit, which is further described in Section 4.2.

§ 1.2. Problem. This text is concerned with the simulation of existing QKD protocols based on different aspects of quantum mechanics as well as a theoretical investigation of relevant protocols within the area. Simulation is done using the OpenQASM software development kit, Qiskit. Current research largely strive to implement protocols in physical hardware, however there is still a need to run large-scale simulations to obtain a larger picture of the

current landscape and compare the different approaches to QKD in order to understand possibilities for improvement and development of new techniques within the field. Parameters of interest for simulation include the size of the keys generated, the size of the error in the protocol, and number of qubits utilized. Theoretical investigation allows us to further examine the actual properties of the protocols compared such as the specifics of the techniques utilized and security assumptions. Furthermore, the question of whether specific QKD protocols can be modified to allow for device-independtness can be investigated, as well as the possibility of converting uncertainty-based protocols to entanglement-based techniques.

Thus, the thesis tackles the problem of simulating and comparing prominent existing QKD protocols that are of significance in current research, as well as providing a theoretical examination of the protocols with the goal of comparing their general properties and possibilities for extending the same.

§ 1.3. Research Question. To approach the problem stated in the preceding section, we here specify the research questions to be answered in this thesis. The following research questions are identified:

1. How does simulations of prominent QKD protocols compare in terms of size of the keys generated and error in key generation?
2. How can QKD protocols be extended to be diQKD and what is the impact on their efficiency in this case?
3. What are the practical and theoretical benefit and drawbacks of using entanglement for key generation over relying on the Heisenberg uncertainty principle?

The research questions will be addressed by performing simulations in Qiskit as well as through theoretical analysis of the different protocols. Although potentially of great significance, the thesis will not investigate and compare the physical implementation of QKD protocols and the impact of such techniques.

§ 1.4. Related Work (Scientific Basis). A recent survey of advances is QKD was presented in [7], which also investigated other aspects of quantum cryptography such as post-quantum cryptography and multiparty communications protocols. Their article provides a review of existing protocols in this field and discuss properties used in the development and implementation. However, no steps are taken towards comparing the different strategies on a measurable or theoretical level or simulating the different protocols. In another study by Nurhadi and Syambas, some prominent QKD protocols between 1984 and 2013 are compared in terms of their underlying quantum principle, and some of these protocols (BB84, BBM92, and B92) are further analyzed and compared by way of simulation using QuVis [12]. This study provides no theoretical analysis of the protocols and does not discuss any

developments beyond 2018.

Since 2018 a number of advances in the field of QKD has been made. In their article from 2021, Zapatero et al. discuss the most recent developments in the field including both theoretical and experimental properties [14]. Their work also does not provide any simulations but discusses different physical implementations of protocols. Lastly, in an article from 2022, Nadlinger et al. provides an experimental implementation of the device-independent Ekert protocol through which a 95,628 bit key was obtained from 1.5 million Bell pairs during eight hours [10].

§ 1.5. Results and Considerations. *TBA*

2. QUANTUM INFORMATION THEORY

§ 2.1. Overview. In the following chapter, we aim to introduce to the unfamiliar reader the fundamentals of quantum information theory and of key distribution schemes in the area of quantum cryptography. The perspective here taken loosely follows the presentation given in [11], although it presents the material from a fairly mathematically heavy perspective. The reader is expected to be familiar with linear algebra, the fundamentals of operator algebras, basic number theory, as well as elementary notions in theoretical computer science. For a complete reference on these topics necessary to understand the following material, the reader is advised to consult [11].

In Section 2.2 we cover the basic notions of quantum information theory from the perspective of theoretical computer science, presenting the mathematical model upon which it is based, elementary gates and operations, as well as measurements and entangled qubits. Section 2.3 introduces the concept of entanglement and quantum non-local games which is used in our later endeavors both to generate keys as well as to verify the existence of entanglement. These are the main building blocks of the thesis and are necessary to both understand the historical as well as the theoretical background on which protocols in QKD are built.

§ 2.2. Quantum Information Theory. Analogously to the classical theory of computing, the smallest unit of computing is defined as a bit, more specifically as a *qubit*, in quantum information theory. However, there are a number of differences between how the classical bit and the quantum bit are modeled. Most crucially, a qubit represents the *state* of a physical system, such as the polarization of a photon or the two states of an electron orbiting an atom, which is modeled mathematically as a unit vector in the Hilbert space \mathbb{C}^2 :

Definition 2.1. A *qubit* representing a quantum state is a unit vector in \mathbb{C}^2 ,

and is denoted using ket-notation as

$$|\psi\rangle = \alpha |0\rangle + \beta |1\rangle,$$

where $|\alpha|^2 + |\beta|^2 = 1$ and the symbols $|0\rangle$ and $|1\rangle$ denotes the so-called *fundamental states* which corresponds to the usual orthonormal basis in \mathbb{C}^2 , i.e.

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

Notably, a qubit does not only have two possible states – 0 or 1 in the classical case – but is also allowed to be in a mix of the two. In particular, if both α and β are non-zero, the state is said to be in *superposition*. Although it might thus appear that a quantum state can hold more information than a classical state in that it can be in a mix of both the fundamental states simultaneously, this is not really the case as the postulates of quantum mechanics tells us that should we wish to retrieve the value of the constants α and β in $|\psi\rangle$ above, the state collapses into either one of the two fundamental states with probability $|\alpha|^2$ or $|\beta|^2$, respectively. This occurs through the process of *measurement* that we shall soon discuss in more detail.

Continuing the analogue to classical systems, we may construct registers of quantum bits:

Definition 2.2. An *n-qubit system* is given by a unit vector in the space $\mathbb{C}^2 \otimes \dots \otimes \mathbb{C}^2 = (\mathbb{C}^2)^{\otimes n}$.

If $\{|0\rangle_A, |1\rangle_A\}$ denotes the fundamental states of a space \mathbb{C}_A^2 , and similarly $\{|0\rangle_B, |1\rangle_B\}$ denotes the fundamental states of \mathbb{C}_B^2 , then the fundamental states of $\mathbb{C}_A^2 \otimes \mathbb{C}_B^2$ is given by the set $\{|0\rangle_A \otimes |0\rangle_B, |0\rangle_A \otimes |1\rangle_B, |1\rangle_A \otimes |0\rangle_B, |1\rangle_A \otimes |1\rangle_B\}$, which is also denoted by $\{|00\rangle, |01\rangle, |10\rangle, |11\rangle\}$.

Some concluding remarks about registers here. In general, we consider a qubit register of n qubits to be an element of a Hilbert space \mathcal{H} of dimension n^2 . In fact, there is a one to one correspondence between Hilbert spaces of finite dimension n^2 and spaces of the form $(\mathbb{C}^2)^{\otimes n}$, see for example Chapter X of [9] for an introduction of this topic.

The information of a quantum state is, although not directly measurable, still useful through the evolution of the state by applying different quantum gates which ultimately alter the probability of different measurement outcomes. A quantum state, much like a classical system, evolves by applying an operation called a quantum gate. If quantum states are represented by vectors, a quantum gate is represented by linear transformations, or matrices, in the following way:

Definition 2.3. A *quantum gate* on a state in the space $(\mathbb{C}^2)^{\otimes n}$ is a unitary transformation from this space to itself.

We choose unitary transformations to represent quantum gates for the simple reason that such transformations preserves the property of being a unit vector, hence ensuring that a quantum state is transformed into another. Interestingly, since unitary linear transformations are invertible, it follows from this definition that quantum gates are *reversible*.

Example 2.4 (CNOT). One commonly applied quantum gate is the *controlled-NOT* gate which is applied to a two qubit state. One qubit in the state in this scenario is the control qubit and the other is the target qubit. The effect of applying this operation is to flip the value of the target qubit if and only if the control qubit is $|1\rangle$. This gate is given by the following matrix:

$$\text{CNOT} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

This operation resembles a classical XOR gate in that the result in the target qubit is the XOR of the control and target qubit.

Example 2.5 (The Hadamard transform). Another common operation is the *Hadamard transform*, which on a single-qubit system is given by the matrix

$$H = \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}.$$

This gate has the notable effect that it transforms the standard basis of the fundamental states $\{|0\rangle, |1\rangle\}$ to $\frac{1}{\sqrt{2}} \left\{ \begin{bmatrix} 1 \\ 1 \end{bmatrix}, \begin{bmatrix} 1 \\ -1 \end{bmatrix} \right\}$, and back again. This basis is also frequently denoted $\{|+\rangle, |-\rangle\}$.

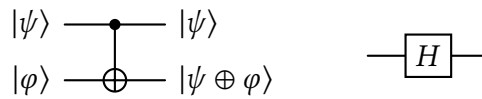


Figure 1: Circuits representing the CNOT and Hadamard gates.

Much like in classical computation, qubits and operations on these can be represented using circuits, which are used to give a pictorial representation of the transformations performed. Our notation in this regard follows that of [11]. Figure 1 shows the circuits representing the CNOT and Hadamard gate.

The final concept in need to be introduced is the notion of quantum measurements. Due to the peculiar nature of quantum physics, the actual value,

i.e. the values of the coefficients of the linear combination of the fundamental states, cannot be directly retrieved from the state. Though, through a measurement process of the state its value can be, at least partially, obtained. This process is constrained by the postulates of quantum mechanics:

Definition 2.6 (The Born rule). Measurement of the quantum state $|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$ results in an observation of the fundamental state $|0\rangle$ or $|1\rangle$ with probability $|\alpha|^2$ or $|\beta|^2$, respectively.

This postulate extends in the expected way to multi-qubit states. The Born rule postulates that a quantum measurement effectively collapses the state to either one of the fundamental states according to some probability distribution. We formally define measurements as follows:

Definition 2.7. Let $|\psi\rangle$ be a quantum state in $(\mathbb{C}^2)^{\otimes n}$, and let $[n] = \{1, \dots, n\}$ be a set of outcomes. Then, a *projective valued measurement (PVM)* is a collection of self-adjoint projections $\{P_i\}_{i \in [n]}$ such that $\sum_{i=1}^n P_i = \mathbb{1}$. The probability of observing outcome i upon measuring $|\psi\rangle$ is given by

$$\|P_i |\psi\rangle\|^2 = \langle \psi | P_i^* P_i | \psi \rangle = \langle \psi | P_i | \psi \rangle,$$

upon which the state collapses to

$$\frac{P_i |\psi\rangle}{\sqrt{\langle \psi | P_i | \psi \rangle}}.$$

The specific kind of measurement we rely on in this thesis are the projective valued measurements. In the theory of quantum mechanics, there are also other types of measurements, that, although the general principle remains the same in that they all adhere to the Born rule, *some text here that motivates this choice of measurement.*



Figure 2: Circuit representation of applying a measurement.

The most surprising property of quantum mechanics, which puzzled researchers for decades, is that of *entanglement*. It is this concept that we will later utilize to create systems of perfectly correlated but separated systems which can be used to securely distribute keys.

As we have seen in the definition of multi-qubit systems, these systems are unit vectors in the space $(\mathbb{C}^2)^{\otimes n}$. However, not all unit vectors in this space can be written as a tensor product of unit vectors from the n individual Hilbert spaces \mathbb{C}^2 . Such states nonetheless exist and are said to be *entangled*. We

now give an example of such a state, that will be of great significance in later sections.

Example 2.8 (Bell-pair). Consider the qubits $|0\rangle$ and $|0\rangle$ forming the two-qubit register $|00\rangle$ in $\mathbb{C}^2 \otimes \mathbb{C}^2$. To this state, we apply two consecutive gates – first the Hadamard transform, and then the CNOT gate – to obtain the following state:

$$\text{CNOT}(H \otimes \mathbb{1}) |00\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}.$$

This sequence of operations can be represented by the circuit in Figure 3. The resulting state is entangled and is often called a *Bell-pair*.

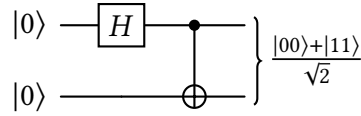


Figure 3: Quantum circuit for creating a Bell-pair.

Crucially, when we measure an entangled state, the involved qubits no longer behave like independent systems, but rather the resulting measurement outcomes are closely correlated. For example, considering the Bell-pair defined above, upon applying the measurement given by the PVM

$$\left\{ \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}, \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix} \right\},$$

to the first qubit, one observes $|0\rangle$ in this qubit with probability $\frac{1}{2}$. In this case, the state in its entirety would collapse to $|00\rangle$, since this is the only viable outcome. Thus, without measuring we immediately know that the second qubit also is $|0\rangle$. Conversely, if $|1\rangle$ is observed in the first qubit after measurement, the second qubit must also be $|1\rangle$.

§ 2.3. Non-local Games. Finally, we cover some theory on so-called *non-local games*. These can be understood as theoretical constructs used for realizing the impact of quantum entanglement in computation. Such games have also been used to experimentally prove the existence of entanglement [13], which is their primary use in the area of QKD.

These games are modeled as taking place between two cooperating “players” that operate at a large distance, making communication through classical channels during the course of the game unfeasible. Typically, the players of the games are referred to as Alice and Bob and a verifier, or *referee*, is introduced to present the players with input and decide if they win the game based on their respective outputs. In its most general form, non-local games can be defined as follows:

Definition 2.9. A non-local game, $\mathcal{G}(V, \pi)$, between players A and B is given by the following parameters:

- Question sets $[n_A]$ and $[n_B]$,
- answer sets $[m_A]$ and $[m_B]$,
- a probability function $\pi : [n_A] \times [n_B] \rightarrow [0, 1] \subset \mathbb{R}$, and
- a function $V : [m_A] \times [m_B] \times [n_A] \times [n_B] \rightarrow \{0, 1\}$.

Typically, we write $V(a, b \mid x, y)$ in place of $V(a, b, x, y)$ where $(a, b) \in [m_A] \times [m_B]$ and $(x, y) \in [n_A] \times [n_B]$ to indicate that this value represents the result of running the game with outputs (a, b) given inputs (x, y) .

The referee selects the input questions (x, y) based on the probability function π , and distributes x to player A and y to player B . Both players return some output value, a from Alice and b from Bob upon which the referee decides if they win the game if $V(a, b \mid x, y) = 1$. Crucially, the players are allowed to discuss a common strategy before the start of the game in order to maximize their winning probability.

One option for Alice and Bob in this scenario is to rely on a purely deterministic choice of output based on the given input, or they may use a randomized procedure. However, they may also decide on a quantum strategy involving the use of a shared, entangled, quantum state. As we will see, for some games, a quantum strategy can result in a greater probability of winning the game compared to a classical strategy.

We now present one of the most significant examples of a non-local game, which is the *CHSH game*, so named after physicists John Clauser, Michael Horne, Abner Shimony, and Richard Holt which first introduced it [4].

Example 2.10 (The CHSH game). Let $[n_A] = [n_B] = [m_A] = [m_B] = \{0, 1\}$, π be the uniform probability distribution on $[n_A] \times [n_B]$ and define

$$V(a, b \mid x, y) = \begin{cases} 1 & \text{if } a \oplus b = x \wedge y \\ 0 & \text{otherwise.} \end{cases}$$

By considering the properties of logical operations, we can observe that $x \wedge y = 0$ for all cases except when $x = y = 1$, while $a \oplus b = 0$ only when $a = b$. Therefore, an optimal and fully deterministic strategy for Alice and Bob is to decide to always return 0 (or 1), independent of their input. This leads to a winning probability of $\frac{1}{4}$.

Alternatively, if Alice and Bob decide to use a quantum strategy for winning the game, they can choose to share an entangled Bell state $|\psi\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$, and select the PVMs corresponding to measurements in the bases $\{|0\rangle, |1\rangle\}$ if $x = 0$ and $\{\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle), \frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)\}$ if $x = 1$ for Alice, and the

measurement bases $\{\cos \frac{\pi}{8} |0\rangle + \sin \frac{\pi}{8} |1\rangle, -\sin \frac{\pi}{8} |0\rangle + \cos \frac{\pi}{8} |1\rangle\}$ if $y = 0$ and $\{\cos \frac{\pi}{8} |0\rangle - \sin \frac{\pi}{8} |1\rangle, \sin \frac{\pi}{8} |0\rangle + \cos \frac{\pi}{8} |1\rangle\}$ if $y = 1$ for Bob. The corresponding PVMs are denoted by P_i^j and Q_i^j for $i, j \in \{0, 1\}$, respectively.

With this strategy if, for example, the given input is $x = y = 0$, the probability of Alice and Bob winning the game is given by the combined probability of the two players measuring and both observing 0 or 1, i.e.

$$\langle \psi | P_0^0 \otimes Q_0^0 | \psi \rangle + \langle \psi | P_1^0 \otimes Q_1^0 | \psi \rangle = \cos^2 \frac{\pi}{8} \approx 0.85.$$

In fact, it can be shown that this is the optimal winning probability of this, and in fact any, quantum strategy for this game. This result is known as Tsirelson's bound [3].

3. QUANTUM KEY DISTRIBUTION

§ 3.1. Overview.

4. METHODOLOGY

§ 4.1. Research Strategy. We recall that the research questions addressed in this thesis as stated in Section 1.3 are:

1. How does simulations of prominent QKD protocols compare in terms of size of the keys generated and error in key generation?
2. How can QKD protocols be extended to be diQKD and what is the impact on their efficiency in this case?
3. What are the practical and theoretical benefit and drawbacks of using entanglement for key generation over relying on the Heisenberg uncertainty principle?

To address these questions, we choose to employ a experimental research strategy as discussed in [5]. An experimental study will allow us to generate quantitative data through simulations and theoretical analysis which can be used to answer the questions as posed. Firstly, experimental simulations in Qiskit will produce data that can clearly demonstrate the size of the keys generated from different protocols and techniques as the number of qubits increase, as well as the impact on error rates. Furthermore, based on a theoretical analysis of possible modifications to existing protocols, quantitative data can be produced through subsequent experiments to compare the impact of using different quantum techniques as a basis for protocols in QKD, thus answering question four.

An experimental approach is taken in favor of other strategies since the primary goal is to produce data from controlled simulations of protocols in QKD in order to deduce the impact and relationship between certain properties. Through experiments, a neutral view in which the impact of the parameters of interest can be obtained in order to draw conclusions on the efficiency and correctness of different approaches. This further opens up for testing new approaches to existing protocols. This approach is also repeatable in that the source code of the simulation will be provided in the report as a means for further research into the area.

The output of conducted experiments will be numerical quantitative data corresponding to the investigated variables, due to the experiments being simulations of executing the QKD protocols for varying parameters.

The research process will proceed in several stages, the first of which is data collection by implementing the identified QKD protocols in Qiskit and run simulations. In this stage, a theoretical analysis of the protocols will also be carried out in order to identify whether it is possible to modify existing QKD protocols into diQKD, after which further experiments are performed. Next, the resulting data is prepared and explored in order to identify possible trends

and identify suitable statistics. Then, proper data analysis will be performed in order to produce descriptive statistics that can be used to answer the research questions. The statistics will then be presented in the form of plots and tables showing the relevant results. The remainder of this chapter will discuss the details of these stages.

§ 4.2. Software Use and Implementation.

§ 4.3. Dataset Compilation / Collection / Synthesis.

§ 4.4. Data Analysis.

§ 4.5. Alternative Research Strategies.

§ 4.6. Validity and Reliability.

§ 4.7. Ethical Considerations.

5. MAIN RESULTS

6. COMPARISON WITH EXISTING WORK

7. CONCLUSION

§ 7.1. Related Work.

§ 7.2. Delimitations.

§ 7.3. Ethical Implications.

§ 7.4. Consideration for Future Work.

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