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Quantum assisted Secure Multiparty Computation

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Abstract

Start with no indent.

Then you can write another paragraph.

Key-words: quantum cryptography, quantum oblivious transfer, quantum obliious linear evaluation, secure multiparty computation.

Resumo

Escrever a mesma coisa que está no Abstract, mas em Português.

Palavras-chave: criptografia quântica, passeios quânticos, memórias quânticas, transições de fase topológicas, estados de fronteira

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Write the acknowledgments here.

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I dedicate this thesis to my loving wife Teresinha and my two children Henrique and Helena who came to life during this journey to help me finish it.

Contents

Abstract	iii
Resumo	v
Acknowledgements	vii
List of Figures	xiii
List of Tables	xv
List of Abbreviations	xvii
1 Introduction	1
2 Technical Overview	7
2.1 Mathematical preliminaries	7
2.2 Secure Multiparty Computation	7
2.2.1 Boolean approach	7
2.2.2 Arithmetic approach	8
2.3 Quantum Information	8
2.3.1 Quantum states representation	8
2.3.2 Entropy	8
2.3.3 Two-universal functions	8
2.3.4 Mutually Unbiased Basis	8
2.4 Universal Composability	8
2.5 Functionality definitions	8
3 Quantum Oblivious Transfer	9
3.1 Impossibility results	10
3.2 BBES-based protocols	11
3.2.1 BBES protocol	12
3.2.2 BBES in the \mathcal{F}_{COM} -hybrid model	15
3.2.3 BBES in the limited-quantum-storage model	18
3.2.4 Bounded-quantum-storage model	18
3.2.5 Noisy-quantum-storage model	20

3.2.6	Hacking attacks to QOT	23
	Bibliography	36

List of Figures

3.1	BBCS OT protocol.	13
3.2	BBCS OT protocol in the $\mathcal{F}_{\mathbf{COM}}$ -hybrid model.	15
3.3	BBCS OT protocol in the bounded-quantum-storage model.	19
3.4	BBCS OT protocol in the noisy-quantum-storage model.	22

List of Tables

List of Abbreviations

A – Alice

B – Bob

BCS – Bardeen-Cooper-Schrieffer

BG – Boltzmann-Gibbs

CS – Chiral symmetry

DTQW – Discrete-time quantum walk

DQPT – Dynamical quantum phase transition

E – Eve

EB – Entanglement based

LE – Loschmidt Echo

MDM – Massive Dirac model

PHS – Particle-hole symmetry

PT – Phase transition

PM – Prepare and measure

SSH – Su-Schrieffer-Heeger

TI – Topological insulator

TSC – Topological superconductor

TRS – Time-reversal symmetry

QKD – Quantum Key Distribution

QW – Quantum walk

Chapter 1

Introduction

The emerging fields of Data Mining and Data Analysis have deeply benefited from the increasing power of computers [1]. However, its need for a massive and methodical collection of data can lead to the complete or partial leak of private sensitive information, such as in the case of the genomics field [2–5]. As a consequence, the aggregation of data from different sources is most of the times blocked due to legally imposed regulations such as the General Data Protection Regulation (GDPR) [6]. Although this has the benefit of protecting people’s privacy, it also has the downside of preventing honest players from accessing data necessary to tackle some of the most important issues in our society.

Secure Multiparty Computation

To overcome the privacy-related issues described above, several privacy-enhancing technologies have been proposed [7–9]. One important area of research is Secure Multiparty Computation (SMC). This technology allows a set of n parties P_i to jointly compute some function $f(x_1, \dots, x_n) = (y_1, \dots, y_n)$ without disclosing their inputs to the other parties. The security requirements of SMC are equivalent to an ideal case, where every party P_i sends his inputs to some independent and trusted third party, who computes $f()$ and sends back to each party their corresponding output.

Since Yao seminal work [10], several SMC protocols have been developed, rendering different framework implementations [11–13]. However, they can generally be separated into two types according to the circuit logic being used: boolean or arithmetic. In each case, the efficiency and security of SMC heavily rely on the efficiency and security of important cryptographic primitives. Boolean-based SMC protocols rely on Oblivious Transfer (OT) [14] and arithmetic-based rely on Oblivious Linear Evaluation (OLE) [15]. Impagliazzo and Rudich [16] proved that both OT and OLE protocols require public cryptography and cannot just rely on symmetric cryptography. This is an unfortunate

result both from an efficiency and security perspective. Indeed, symmetric cryptography is lighter than asymmetric cryptography and requires less computational assumptions. Moreover, with the emergence of quantum computers, Shor’s algorithm [17] jeopardizes all the current public-key methods based on RSA, Elliptic Curves or Diffie-Hellman, in which many OT and OLE implementations rely on. This puts at risk the deployment of classical OT and OLE, which ultimately leads to the exposure of the SMC parties’ private inputs. Thus, it is essential to develop SMC methods secure against quantum computers while not compromising state-of-the-art performance levels.

A Quantum Era

We are now in the beginning of what is known to be the second quantum revolution. Quantum technology has evolved to a point where we can integrate quantum exotic features into complex engineering systems. Most of the applications lie in the field of quantum cryptography, where one thrives to find protocols that offer some advantage over their classical counterparts. As analysed in [18, 19], these advantages can be of two types:

1. Improve the security requirements, rendering protocols that are information-theoretically secure or require fewer computational assumptions;
2. Achieve new primitives that were previously not possible just with classical techniques.

Despite the most famous use-case of quantum cryptography being quantum key distribution (QKD), other primitives play an important role in this quest. Some examples of these cryptographic tasks are bit commitment [20], coin flipping [21], delegated quantum computation [22], position verification [23], and password-based identification [24, 25].

Also, the intrinsic randomness provided by quantum phenomena is an ideal resource to develop quantum communication protocols for oblivious transfer (OT) [26]. Remarkably, there is a distinctive difference between classical and quantum OT from a security standpoint, as the latter is proved to be possible assuming only the existence of quantum-hard one-way functions [27, 28]. This means quantum OT can be based only on symmetric cryptography, requiring weaker security assumptions than classical OT. Moreover, these quantum protocols frequently have a desirable property that guarantees information-theoretic security after the execution of the protocol. This property is commonly called everlasting security. This greatly improves the security of SMC protocols, allowing them to have their security based on symmetric cryptography alone and with this important feature of everlasting security. Regarding oblivious linear evaluation (OLE) primitive, it is known that it can be reduced to OT [29] through classical methods that do not require further

assumptions. Therefore, it seems natural to use quantum OT to generate quantum-secure OLE instances.

Contributions and Outline

Despite the many advances, the adoption of quantum cryptography by secure multiparty computation (SMC) systems is still reduced. This is due to the efficiency challenges imposed by quantum technology and the need of high throughput of both OT and OLE primitives in boolean- and arithmetic-based SMC, respectively.

The overall goal of this dissertation is to give one step closer to the adoption of quantum cryptography by SMC systems. We do this with three contributions. In our first contribution, we start the studying of comparing the efficiency of both classical and quantum protocols. Our second contribution is the first quantum OLE protocol which does not rely on OT. Our last contribution is an implementation of a special-purpose SMC system applied to genomics analysis assisted with quantum OT. Along the way, we produced a review dedicated to quantum OT protocols alone. Usually, its analysis is integrated into more general surveys under the topic of “quantum cryptography”, leading to a less in-depth exposition of the topic.

We describe the contributions in a bit more detail.

Efficiency of classical and quantum OT protocols. To the best of our knowledge, there is no comparative study on the efficiency of quantum and classical approaches. This is mainly caused by two reasons. From a theoretical perspective, the use of different types of information (quantum and classical) makes it difficult to make a fair comparison based on the protocols’ complexity. Also, from a practical standpoint, there is still a discrepancy in the technological maturity between quantum and classical techniques. Quantum technology is still in its infancy, whereas classical processors and communication have many decades of development.

Despite these constraints, we compare the complexity and operations efficiency of classical and quantum protocols. To achieve this, we realize that both classical and quantum protocols can be divided into two phases: offline and online. The offline phase is characterized by the fact that it is independent of the parties’ inputs. This means that, from a practical point-of-view, this phase produces the resources necessary to use during the online phase, where we take into consideration the parties’ inputs. It can be argued that the offline phase is not so hungry-efficient as the online phase. As a consequence, for comparison purposes, we can focus on the online phase. Fortunately, the online phase of quantum OT is solely based on classical communications. Therefore, it is possible and

fair to compare the online phase of both classical and quantum protocols.

We make a detailed comparison between the complexity of the online phase of two state-of-the-art classical OT protocols [30, 31] and an optimized quantum OT protocol. We conclude that the online phase of quantum OT competes with its classical counterparts and has the potential to be more efficient.

Quantum oblivious linear evaluation protocol. Our second contribution is a quantum protocol for OLE with quantum universally composable (quantum-UC) security in the \mathcal{F}_{COM} -hybrid model, i.e. when assuming the existence of a commitment functionality, \mathcal{F}_{COM} . To obtain a secure protocol, we take advantage of the properties of Mutually Unbiased Bases in high-dimensional Hilbert spaces with prime and prime-power dimension. Such a choice is motivated by recent theoretical and experimental advances that pave the way for the development and realization of new solutions for quantum cryptography [32–36].

To the best of our knowledge our protocol is the first quantum-UC secure quantum OLE proposal. Moreover, it is not based on any quantum OT implementation which would be the standard approach. We consider the static corruption adversarial model with both semi-honest and malicious adversaries. We develop a weaker version of OLE, which may be of independent interest. We also modify the proposed protocol to generate quantum-UC secure vector OLE (VOLE). We give bounds on the possible size of VOLE according to the security parameters.

Quantum assisted secure multiparty computation. Individuals’ privacy and legal regulations demand genomic data be handled and studied with highly secure privacy-preserving techniques. In this contribution, we propose a feasible secure multiparty computation (SMC) system assisted with quantum cryptographic protocols that is designed to compute a phylogenetic tree from a set of private genome sequences. This system adapts several distance-based methods (Unweighted Pair Group Method with Arithmetic mean, Neighbour-Joining, Fitch-Margoliash) into a private setting where the sequences owned by each party are not disclosed to the other members present in the protocol. We do not apply a generic implementation of SMC to the problem of phylogenetic trees. Instead, we develop a tailored private protocol for this use case in order to improve efficiency.

We theoretically evaluate the performance and privacy guarantees of the system through a complexity analysis and security proof and give an extensive explanation about the implementation details and cryptographic protocols. We also implement a quantum-assisted secure phylogenetic tree computation based on the Libscapi implementation of the Yao protocol, the PHYLIP library and simulated keys of two quantum systems: quantum

oblivious key distribution and quantum key distribution.¹. This demonstrates its effectiveness and practicality. We benchmark our implementation against a classical-only solution and we conclude that both approaches render similar execution times. The only difference between the quantum and classical systems is the time overhead taken by the oblivious key management system of the quantum-assisted approach.

The results are presented as follows. We start presenting SMC protocols based on OT and OLE at Chapter 2. Then, at Chapter 3 we introduce some quantum information concepts and security definitions used throughout the thesis. Chapter 4 is devoted to quantum oblivious transfer protocols. Then, in Chapter 5 we compare classical and quantum approaches for OT. In Chapter 6 we present our quantum OLE protocol along with its security proof. Finally, in Chapter 7, we presented our implementation of quantum-assisted SMC system applied to phylogeny analysis.

Published research

This thesis is based on research published in various journals. During my PhD I was involved in the following projects.

- [37] Manuel B. Santos, Paulo Mateus, and Armando N. Pinto. “Quantum Oblivious Transfer: A Short Review”. In: *Entropy* 24.7 (July 2022), p. 945.
- [37] Manuel B. Santos, Armando N. Pinto, and Paulo Mateus. “Quantum and classical oblivious transfer: A comparative analysis”. In: *IET Quantum Communication* 2.2 (May 2021), pp. 42–53.
- [38] Manuel B. Santos, Paulo Mateus, and Chrysoula Vlachou. Quantum Universally Composable Oblivious Linear Evaluation. 2022. DOI: 10.48550/ARXIV.2204.14171. Poster at QCrypt2022.
- [39] Manuel B. Santos et al. “Private Computation of Phylogenetic Trees Based on Quantum Technologies”. In: *IEEE Access* 10 (2022), pp. 38065–38088.
- [40] Manuel B. Santos et al. “Quantum Secure Multiparty Computation of Phylogenetic Trees of SARS-CoV-2 Genome”. In: *2021 Telecoms Conference (ConfTELE)*. IEEE, Feb. 2021.
- [41] Armando N. Pinto et al. “Quantum Enabled Private Recognition of Composite Signals in Genome and Proteins”. In: *2020 22nd International Conference on Transparent Optical Networks (ICTON)*. IEEE, July 2020.

¹The code can be accessed at the following repo: <https://github.com/manel1874/QSHY/tree/dev-cq-phyliip>

Chapter 4 is based on [37]. Chapter 5 is based on the work developed on both [37] and [39]. Chapter 6 presents all the results from [38]. Finally, Chapter 7 is the combination of [39–41]

Chapter 2

Technical Overview

2.1 Mathematical preliminaries

Recall, we use the notation $s \leftarrow_{\S} S$ to describe a situation where an element s is drawn uniformly at random from the set S .

Throughout this thesis, Alice plays the role of the sender and Bob plays the role of the receiver.

2.2 Secure Multiparty Computation

Estrutura da introdução:

- Comentar que não sabemos mais do que o output da computação. Dar o exemplo da média de pesos. 2 pessoas sabemos o resultado. 3 já não. Ainda assim, pode revelar alguma coisa a mais. Note that, practically, we can put together other PET such as Differential Privacy in order to do this.

Talk about two approaches: boolean and arithmetic. Discuss the advantages and disadvantages of each.

2.2.1 Boolean approach

Boolean approach is based on the Yao protocol. In order to do it we need OT. We start by presenting OT and then we describe the Yao protocol.

Oblivious Transfer

The study of oblivious transfer (OT) has been very active since its first proposal in 1981 by Rabin [42]. The importance of OT comes from its wide number of applications. More specifically, one can prove that OT is equivalent to the secure two-party computation of

general functions [10, 14], i.e. one can implement a secure two-party computation using OT as its building block. Additionally, this primitive can also be used for secure multi-party computation (SMC) [29], private information retrieval [43], private set intersection [44], and privacy-preserving location-based services [45].

Definition

Small classical review

Base OT vs Extended OT

Yao protocol

Description

Optimizations

Security

Generalizations of Yao: GMW, BMR

2.2.2 Arithmetic approach

Oblivious Linear Evaluation

SPDZ

2.3 Quantum Information

2.3.1 Quantum states representation

2.3.2 Entropy

2.3.3 Two-universal functions

2.3.4 Mutually Unbiased Basis

2.4 Universal Composability

2.5 Functionality definitions

Chapter 3

Quantum Oblivious Transfer

In a recent survey on classical oblivious transfer (OT) [46], all the analysed protocols require some form of asymmetric cryptography. Indeed, in the classical setting, it is impossible to develop information-theoretic secure OT or even reduce it to one-way functions, requiring some public-key computational assumptions. As shown by Impagliazzo and Rudich [47], one-way functions (symmetric cryptography) alone do not imply key agreement (asymmetric cryptography). Also, Gertner et al. [48] pointed out that since it is known that OT implies key agreement, this sets a separation between symmetric cryptography and OT, leading to the conclusion that OT cannot be generated alone by symmetric cryptography. Otherwise, one could use one-way functions to implement key agreement through the OT construction. This poses a threat to all classical OT protocols [49–51] that are based on mathematical assumptions provably broken by a quantum computer [17]. Besides the security problem, asymmetric cryptography tends to be computationally more complex than symmetric cryptography, creating a problem in terms of speed when a large number of OTs are required. The classical post-quantum approach, thrives to find protocols resistant against quantum computer attacks. However, these are still based on complexity problems and are not necessarily less computationally expensive, than the previously mentioned ones.

In parallel to the classical post-quantum approach, the quantum cryptography community tackled this security issue by presenting some OT protocols based on quantum technologies. Intriguingly enough, more than a decade before the first classical OT by Rabin (1981, [42]) was published, Wiesner proposed a similar concept. However, at the time, it was rejected for publication due to the lack of acceptance in the research community. The first published quantum OT (QOT) protocol, known as the BB84 (Bennett-Brassard-Cr peau-Skubiszewska) protocol [26] was only presented in 1992. Remarkably, there is a distinctive difference between classical and quantum OT from a security standpoint, as the latter is proved to be possible assuming only the existence of quantum-hard one-way

functions [27, 28]. This means quantum OT requires weaker security assumptions than classical OT.

In this chapter, we review the particular topic of quantum OT. We mainly comment on several important OT protocols, their underlying security models and assumptions. To the best of our knowledge, there is no prior survey dedicated to quantum OT protocols alone. Usually, its analysis is integrated into more general surveys under the topic of “quantum cryptography”, leading to a less in-depth exposition of the topic. For reference, we provide some distinctive reviews on the general topic of quantum cryptography [18, 52–58].

This chapter is divided as follows. We start by giving a brief overview of the impossibility results related to quantum OT. Then, we provide an exposition about some of the most well-known quantum OT protocols based on assumptions. Finally, we give a brief overview of OT protocols not covered throughout this thesis.

3.1 Impossibility results

The beginning of the development of quantum OT (QOT) came hand in hand with the development of quantum bit commitment (QBC). In fact, the first proposed QOT protocol (BBCS [26]) reduces QOT to QBC. This sets a distinctive difference between classical and quantum protocols. Although bit commitment (BC) can be reduced to oblivious transfer (OT) [14], the reverse is not true using only classical communication [59]. Therefore, Yao’s proof [60] of BBCS protocol [26] gives quantum communications the enhanced quality of having an equivalence between QOT and QBC - they can be reduced to each other - a relation that is not known in the classical realm.

At the time of the BBCS protocol, the quest for unconditionally secure QOT was based on the possibility of unconditional secure QBC. A year later, Brassard et al. presented a QBC protocol [61] named after the authors, BCJL (Brassard-Crépeau-Jozsa-Langlois). However, this work presented a flawed proof of its unconditional security which was generally accepted for some time, until Mayers spotted an issue on it [62]. Just one year after, Lo and Chau [63], and Mayers [64] independently proved unconditional QBC to be impossible. Nevertheless, the existence of unconditionally secure QOT not based on QBC was still put as an open question [52] even after the so-called no-go theorems [63, 64]. However, Lo was able to prove directly that unconditionally secure QOT is also impossible [65]. He concluded this as a corollary of a more general result that states that secure two-party computations which allow only one of the parties to learn the result (one-side secure two-party computation) cannot be unconditionally secure. Lo’s results triggered a line of research on the possibility of two-sided secure two-party computation (both parties are allowed to learn the result without having access to the other party’s inputs), which

was also proved by Colbeck to be impossible [66] and extended in subsequent works [67–69]. For a more in-depth review of the impossibility results presented by Lo, Chau and Mayers, we refer the interested reader to the following works [59, 70].

Although the impossibility results have been well accepted in the quantum cryptography community, there was some criticism regarding the generality of the results [71–74]. This line of research reflects the view put forward by Yuen [71] in the first of these papers: “Since there is no known characterization of all possible QBC protocols, logically there can really be no general impossibility proof, strong or not, even if it were indeed impossible to have an unconditionally secure QBC protocol.” In parallel, subsequent analyses were carried out, reaffirming the general belief of impossibility [75–77]. However, most of the discord has ended with Ariano et al. proof [78] in 2007, giving an impossibility proof covering all conceivable protocols based on classical and quantum information theory. Subsequent work digested Ariano et al. [78] work, trying to present more succinct proofs [79–81] and to translate it into categorical quantum mechanics language [82–84].

Facing these impossibility results, the quantum cryptography community followed two main paths:

1. Develop OT protocols under some assumptions. These could be based on limiting the technological power of the adversary (e.g. noisy-storage model, relativistic protocols, isolated-qubit model) or assuming the security of additional functionalities (e.g. bit commitment).
2. Develop OT protocols with a relaxed security definition. These allow the adversary to extract, with a given probability, some information (partial or total) about the honest party input/output. This approach leads to the concepts of weak OT and weak private database query.

In the next section, we explore protocols that produce a special primitive called *oblivious keys* as an intermediate step.

3.2 BBCS-based protocols

In this section, we explore protocols that circumvent the no-go theorems [63, 64] through assumptions. Some of the presented solutions are based on one-way functions, which are believed to be quantum-hard [27, 28, 85], and others rely on technological or physical limitations of the adversaries [86–91]. The latter are qualitatively different from complexity-based assumptions on which post-quantum protocols rely. Also, all these assumptions have the important property that they only have to hold during the execution of the protocol for its security to be preserved. In other words, even if the assumptions

lose their validity at some later point in time, the security of the protocol is not compromised. This property is commonly known as *everlasting* security [92]. Everlasting security is also a major distinctive feature of quantum protocols when compared with classical cryptographic approaches.

We start by presenting the first QOT protocol. Then, we see how this protocol led to the development of two assumption models: \mathcal{F}_{COM} -hybrid model and the limited-quantum-storage model.

3.2.1 BB84 protocol

Notation conflict: \mathcal{F} to denote universal functions

In 1983, Wiesner came up with the idea of *quantum conjugate coding* [93]. This technique is the main building block of many important quantum cryptographic protocols [24, 94, 95], including quantum oblivious transfer [26]. It also goes under the name of *quantum multiplexing* [95], *quantum coding* [96] or *BB84 coding* [59]. In quantum conjugate coding we encode classical information in two conjugate (non-orthogonal) bases. This allows us to have the distinctive property that measuring on one basis destroys the encoded information on the corresponding conjugate basis. So, when bit 0 and 1 are encoded by these two bases, no measurement is able to perfectly distinguish the states. We will be using the following bases in the two-dimensional Hilbert space \mathcal{H}_2 :

- Computational basis: $+$ $:= \{|0\rangle_+, |1\rangle_+\}$;
- Hadamard basis: \times $:= \{|0\rangle_\times, |1\rangle_\times\} = \left\{ \frac{1}{\sqrt{2}}(|0\rangle_+ + |1\rangle_+), \frac{1}{\sqrt{2}}(|0\rangle_+ - |1\rangle_+) \right\}$.

Protocol [26]. The first proposal of a quantum oblivious transfer protocol is presented in Figure 3.1 and it is called after its creators, Bennett-Brassard-Crépeau-Skubiszewska (BB84). It builds on top of the quantum conjugate coding technique. Alice starts by using this encoding to generate a set of qubits that are subsequently randomly measured by Bob. These two steps make up the first phase of the BB84 QKD protocol. For this reason, this is called the *BB84 phase*. Next, both parties use the output bits obtained from Bob and the random elements generated by Alice to share a special type of key, known as *oblivious key*. This is achieved when Alice reveals her bases θ^A to Bob. Using the oblivious key as a resource, Alice can then obliviously send one of the messages m_0, m_1 to Bob, ensuring that he is only able to know one of the messages. This is achieved using a two-universal family of hash functions \mathcal{F} from $\{0, 1\}^{n/2}$ to $\{0, 1\}^l$. Recall, we use the notation $s \leftarrow_{\$} S$ to describe a situation where an element s is drawn uniformly at random from the set S .

Π^{BBCS} protocol

Parameters: n , security parameter; \mathcal{F} two-universal family of hash functions.

Alice's input: $(m_0, m_1) \in \{0, 1\}^l$ (two messages).

Bob's input: $b \in \{0, 1\}$ (bit choice).

BB84 phase:

1. Alice generates random bits $\mathbf{x}^A \leftarrow_{\$} \{0, 1\}^n$ and random bases $\boldsymbol{\theta}^A \leftarrow_{\$} \{+, \times\}^n$. Sends the state $|\mathbf{x}^A\rangle_{\boldsymbol{\theta}^A}$ to Bob.
2. Bob randomly chooses bases $\boldsymbol{\theta}^B \leftarrow_{\$} \{+, \times\}^n$ to measure the received qubits. We denote by \mathbf{x}^B his output bits.

Oblivious key phase:

3. Alice reveals to Bob the bases $\boldsymbol{\theta}^A$ used during the *BB84 phase* and sets his oblivious key to $\text{ok}^A := \mathbf{x}^A$.
4. Bob computes $\mathbf{e}^B = \boldsymbol{\theta}^B \oplus \boldsymbol{\theta}^A$ and sets $\text{ok}^B := \mathbf{x}^B$.

Transfer phase:

5. Bob defines $I_0 = \{i : \mathbf{e}_i^B = 0\}$ and $I_1 = \{i : \mathbf{e}_i^B = 1\}$ and sends the set I_b to Alice.
6. Alice picks two uniformly random hash functions $f_0, f_1 \in \mathcal{F}$, computes the pair of strings (s_0, s_1) as $s_i = m_i \oplus f_i(\text{ok}_{I_b \oplus i}^A)$ and sends the pairs (f_0, f_1) and (s_0, s_1) to Bob.
7. Bob computes $m_b = s_b \oplus f_i(\text{ok}_{I_0}^B)$.

Alice's output: \perp .

output: m_b .

Figure 3.1: BBCS OT protocol.

Oblivious keys. As we saw in the BBCS protocol, oblivious keys can be used as a resource to produce OT instances. In fact, we can draw a comparison between standard encryption keys and oblivious keys. In the same way as standard keys are the resource that allows the encryption of a specific message, oblivious keys are the resource that enables the performance of OT with messages. In other words, encryption methods consume standard keys, while OT methods consume oblivious keys. The term, oblivious key, was used for the first time by Fehr and Schaffner [97] referring to random OT. However, under

a subtle different concept, it was put forth by Jakobi et al. [98] and used to implement private database queries (PDQ). Also, in a recent work, Lemus et al. [99] presented the concept of oblivious key applied to OT protocols. We can define it as follows.

Definition 1 (Oblivious key). *An oblivious key shared between two parties, Alice and Bob, is a tuple $\text{ok} := (\text{ok}^A, (\text{ok}^B, \mathbf{e}^B))$ where ok^A is Alice's key, ok^B is Bob's key and \mathbf{e}^B is Bob's signal string. \mathbf{e}^B indicates which indexes of ok^A and ok^B are correlated and which indexes are uncorrelated, i.e. $e_i^B = 0$ when the corresponding indexes are correlated and $e_i^B = 1$ when they are not.*

Note that, for some index i , when two index elements ok_i^A and ok_i^B are correlated, $\text{ok}_i^A = \text{ok}_i^B$. However, when they are uncorrelated, they are drawn independently. This means that both index elements may either be equal or different. Consider the following oblivious key $\text{ok} = (001101101101, (000101001100, 101000110001))$ as an example. We can check it is a well structured oblivious key:

$$\left. \begin{array}{l} \text{ok}^A : \begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|} \hline 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 1 \\ \hline \end{array} \\ \text{ok}^B : \begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|} \hline 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ \hline \end{array} \\ \mathbf{e}^B : \begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|} \hline 1 & 0 & 1 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 1 \\ \hline \end{array} \end{array} \right\} \text{ok}$$

It is worth stressing that oblivious keys are independent of the sender's messages m_0, m_1 and are not the same as random OT. In fact, as Alice does not know the groups of indexes I_0 and I_1 computed by Bob after the basis revelation, Alice does not have her messages fully defined. A similar concept was defined by König et al. [88] under the name of *weak string erasure*.

Security. Regarding security, the BBCS protocol is unconditionally secure against dishonest Alice. Intuitively, this comes from the fact that Alice does not receive any information from Bob other than some set of indexes I_0 . However, the BBCS protocol is insecure against dishonest Bob. In its original paper [26], the authors describe a memory attack that provides Bob complete knowledge on both messages m_0 and m_1 without being detected. This can be achieved by having the receiver delay his measurements in step 2 to some moment after step 3. This procedure is commonly called the memory attack as it requires quantum memory to hold the states until step 3. The authors suggest that, for the protocol to be secure, the receiver has to be forced to measure the received states at step 2. In the following sections, we present two common approaches to tackle this issue. We may assume the existence of commitments or set physical assumptions that constrain Bob from delaying his measurement.

3.2.2 BBCS in the \mathcal{F}_{COM} -hybrid model

As mentioned in the previous section, a secure BBCS protocol requires Bob to measure his qubits in step 2. In this section, we follow the suggestion from the original BBCS paper [26] and fix this loophole using a commitment scheme. Since we assume we have access to some commitment scheme, we call it \mathcal{F}_{COM} -hybrid model¹.

$\Pi_{\mathcal{F}_{\text{COM}}}^{\text{BBCS}}$ protocol

Parameters: n , security parameter; \mathcal{F} two-universal family of hash functions.

Alice's input: $(m_0, m_1) \in \{0, 1\}^l$ (two messages).

Bob's input: $b \in \{0, 1\}$ (bit choice).

BB84 phase: Same as in Π^{BBCS} (Figure 3.1).

Cut and choose phase:

3. Bob commits to the bases used and the measured bits, i.e. $\text{COM}(\theta^{\text{B}}, x^{\text{B}})$, and sends to Alice.
4. Alice asks Bob to open a subset T of commitments (e.g. $n/2$ elements) and receives $\{\theta_i^{\text{B}}, x_i^{\text{B}}\}_{i \in T}$.
5. In case any opening is not correct or $x_i^{\text{B}} \neq x_i^{\text{A}}$ for $\theta_i^{\text{B}} = \theta_i^{\text{A}}$, abort. Otherwise, proceed.

Oblivious key phase: Same as in Π^{BBCS} (Figure 3.1).

Transfer phase: Same as in Π^{BBCS} (Figure 3.1).

Alice's output: \perp .

Bob's output: m_b .

Figure 3.2: BBCS OT protocol in the \mathcal{F}_{COM} -hybrid model.

Protocol. The modified BBCS (Figure 3.2) adds a *cut and choose* phase that makes use of a commitment scheme COM to check whether Bob measured his qubits in step 2 or not. It goes as follows. Bob commits to the bases used to measure the qubits in the *BB84 phase* and the resulting output bits. Then, Alice chooses a subset of qubits to be tested and asks Bob to open the corresponding commitments of the bases and output elements. If no inconsistency is found, both parties can proceed with the protocol. Note that the size of the testing subset has to be proportional to n (security parameter), as this guarantees

¹The notation \mathcal{F}_{COM} is commonly used for ideal functionalities. However, here we abuse the notation by using \mathcal{F}_{COM} to refer to any commitment scheme (including the ideal commitment functionality).

that the rest of the qubits were measured by Bob with overwhelming probability in n .

Security. Formally proving the security of this protocol led to a long line of research [25–28, 60, 97, 100–105]. Earlier proofs from the 90’s started by analyzing the security of the protocol against limited adversaries that were only able to do individual measurements [101]. Then, Yao [60] was able to prove its security against more general adversaries capable of doing fully coherent measurements. Although these initial works [60, 101, 102] were important to start developing a QOT security proof, they were based on unsatisfactory security definitions. At the time of these initial works, there was no composability framework [97, 104] under which the security of the protocol could be considered. In modern quantum cryptography, these protocols are commonly proved in some quantum simulation-paradigm frameworks [25, 88, 97, 104]. In these paradigms, the security is proved by showing that an adversary in a real execution of the protocol cannot cheat more than what he is allowed in an ideal execution, which is secure by definition. This is commonly proved by utilizing an entity, called simulator, whose role is to guarantee that a real execution of the protocol is indistinguishable from an ideal execution. Moreover, they measured the adversary’s information through average-case measures (e.g. Collision Entropy, Mutual Information) which are proven to be weak security measures when applied to cryptography [106, 107].

More desirable worst-case measures started to be applied to quantum oblivious transfer around a decade later [108, 109]. These were based on the concept of *min-entropy* [106, 107], H_{\min} , which, intuitively, reflects the maximum probability of an event to happen. More precisely, in order to prove security against dishonest Bob, one is interested in measuring Bob’s min-entropy on Alice’s oblivious key ok^A conditioned on some quantum side information E he may have, i.e. $H_{\min}(\text{ok}^A|E)$. Informally, for a bipartite classical-quantum state ρ_{XE} the conditional min-entropy $H_{\min}(X|E)$ is given by

$$H_{\min}(X|E)_{\rho_{XE}} := -\log P_{\text{guess}}(X|E),$$

where $P_{\text{guess}}(X|E)$ is the probability the adversary guesses the value x maximized over all possible measurements. Damgård et al. [25] were able to prove the stand-alone QOT security when equipped with this min-entropy measure and with the quantum simulation-paradigm framework developed by Fehr and Schaffner [97]. Their argument to prove the security of the protocol against dishonest Bob can be summarized as follows. The cut and choose phase ensures that Bob’s conditional min-entropy on the elements of ok^A belonging to I_1 (indexes with uncorrelated elements between Alice’s and Bob’s oblivious keys) is lower-bounded by some value that is proportional to the security parameter, i.e. $H_{\min}(\text{ok}_{I_1}^A|E) \geq n\lambda$ for some $\lambda > 0$. Note that this is equivalent to derive an upper

bound on the guessing probability $P_{guess}(\text{ok}_{I_1}^A|E) \leq 2^{-n\lambda}$. Having deduced an expression for λ , they proceed by applying a random hash function f from a two-universal family \mathcal{F} , $f \leftarrow_{\$} \mathcal{F}$. This final step ensures that $f(\text{ok}_{I_1}^A)$ is statistically indistinguishable from uniform (privacy amplification theorem [109–111]). The proof provided by Damgård et al. [25] was extended by Unruh [104] to the quantum Universal Composable (UC) model, making use of ideal commitments. Now, a natural question arises:

Which commitment schemes can be used to render simulation-based security?

Commitment scheme. The work by Aaronson [85] presented a non-constructive proof that “indicates that collision-resistant hashing might still be possible in a quantum setting”, giving confidence in the use of commitment schemes based on quantum-hard one-way functions in the $\Pi_{\mathcal{F}_{\text{COM}}}^{\text{BBCS}}$ protocol. Hopefully, it was shown that commitment schemes can be built from any one-way function [112–114], including quantum-hard one-way functions. Although it is intuitive to plug in into $\Pi_{\mathcal{F}_{\text{COM}}}^{\text{BBCS}}$ a commitment scheme derived from a quantum-hard one-way function, this does not necessarily render a simulation-based secure protocol. This happens because the nature of the commitment scheme can make the simulation-based proof difficult or even impossible. For a detailed discussion see [27].

Indeed, the commitment scheme must be quantum secure. Also, the simulator must have access to two intriguing properties: *extractability* and *equivocality*. Extractability means the simulator can extract the committed value from a malicious committer. Equivocal means the simulator can change the value of a committed value at a later time. Although it seems counter-intuitive to use a commitment scheme where we can violate both security properties (hiding and binding properties), it is fundamental to prove its security. Extractability is used by the simulator to prove security against the dishonest sender and equivocality is used by the simulator to prove security against the dishonest receiver. In the literature, there have been some proposals of the commitment schemes *COM* with these properties based on:

- Quantum-hard one-way functions [27, 28];
- Common Reference String (CRS) model [104, 115];
- Bounded-quantum-storage model [116];
- Quantum hardness of the Learning With Errors assumption [25].

Composability. The integration of secure OT executions in secure multiparty protocols [10] should not lead to security breaches. Although it seems intuitive to assume that

a secure OT protocol can be integrated within more complex protocols, proving this is highly non-trivial as it is not clear *a priori* under which circumstances protocols can be composed [117].

The first step towards composability properties is the development of simulation based-security. However, this does not necessarily imply composability (see Section 4.2 of [117] for more details), as a composability framework is also required. In the literature, there have been some proposals for such a framework. In summary, Fehr and Schaffner [97] developed a composability framework that allows sequential composition of quantum protocols in a classical environment. The works developed by Ben-Or and Mayers [118] and Unruh [104, 119] extended the classical Universal Composability model [120] to a quantum setting (quantum-UC model), allowing concurrent composability. Maurer and Renner [121] developed a more general composability framework that does not depend on the models of computation, communication, and adversary behaviour. More recently, Broadbent and Karvonen [84] created an abstract model of composable security in terms of category theory. Up until now, and to the best of our knowledge, the composable security of the protocol $\Pi_{\mathcal{F}_{\text{COM}}}^{\text{BBCS}}$ was only proven in the Fehr and Schaffner model [97] by Damgård et al. [25] and in the quantum-UC by Unruh [104].

3.2.3 BBCS in the limited-quantum-storage model

In this section, we review protocols based on the limited-quantum-storage model. The protocols developed under this model avoid the no-go theorems because they rely their security on reasonable assumptions regarding the storage capabilities of both parties. Under this model, there are mainly two research lines. One was started by Damgård, Fehr, Salvail and Schaffner [86], who developed the bounded-storage model. In this model, the parties can only store a limited number of qubits. The other research line was initiated by Wehner, Schaffner and Terhal [87], who developed the noisy-storage model. In this model the parties can store *all* qubits. However, they are assumed to be unstable, i.e. they only have imperfect noisy storage of qubits that forces some decoherence. In both models, the adversaries are forced to use their quantum memories as both parties have to wait a predetermined time (Δt) during the protocol.

3.2.4 Bounded-quantum-storage model

In the bounded-quantum-storage model or BQS model for short, we assume that, during the waiting time Δt , the adversaries are only able to store a fraction $0 < \gamma < 1$ of the transmitted qubits, i.e. the adversary is only able to keep $q = n\gamma$ qubits. The parameter γ is commonly called the storage rate.

Protocol. The protocol in the BQS model, $\Pi_{\text{bqs}}^{\text{BBCS}}$, is very similar to the BBCS protocol Π^{BBCS} presented in Figure 3.1. The difference is that both parties have to wait a predetermined time (Δt) after step 2. This protocol is presented in Figure 3.3.

$\Pi_{\text{bqs}}^{\text{BBCS}}$ protocol

Parameters: n , security parameter; \mathcal{F} two-universal family of hash functions.
Alice's input: $(m_0, m_1) \in \{0, 1\}^l$ (two messages).
Bob's input: $b \in \{0, 1\}$ (bit choice).

BB84 phase: Same as in Π^{BBCS} (Figure 3.1).

Waiting time phase:

3. Both parties wait time Δt .

Oblivious key phase: Same as in Π^{BBCS} (Figure 3.1).

Transfer phase: Same as in Π^{BBCS} (Figure 3.1).

Alice's output: \perp .
Bob's output: m_b .

Figure 3.3: BBCS OT protocol in the bounded-quantum-storage model.

Security. We just comment on the security against dishonest Bob because the justification for the security against dishonest Alice is the same as in the original BBCS protocol, Π^{BBCS} (see Section 3.2.1).

Under the BQS assumption, the waiting time (Δt) effectively prevents Bob from holding a *large fraction* of qubits until Alice reveals the bases choices θ^A used during the *BB84 phase*. This comes from the fact that a dishonest Bob is forced to measure a fraction of the qubits, leading him to lose information about Alice's bases θ^A .

More specifically, Damgård et al. [109] showed that, with overwhelming probability, the loss of information about Alice's oblivious key ($\text{ok}_{I_1}^A$) is described by a lower bound on the min-entropy [55]

$$H_{\min}(\text{ok}_{I_1}^A | E) \geq \frac{1}{4}n - \gamma n - l - 1.$$

Similarly to the \mathcal{F}_{COM} -hybrid model, the min-entropy value has to be bounded by a

factor proportional to the security parameter n . To render a positive bound, we derive an upper bound on the fraction of qubits that can be saved in the receiver's quantum memory, while preserving the security of the protocol, i.e. $\gamma < \frac{1}{4}$.

The above upper bound was later improved by König et al. [88] to $\gamma < \frac{1}{2}$. The authors also showed that the BQS model is a special case of the noisy-quantum-storage model. Subsequently, based on higher-dimensional mutually unbiased bases, Mandayam and Wehner [122] presented a protocol that is still secure when an adversary cannot store even a small fraction of the transmitted pulses. In this latter work, the storage rate γ approaches 1 for increasing dimension.

Composability. The initial proofs given by Damgård et al. [86, 109] were only developed under the stand-alone security model [123]. In this model the composability of the protocol is not guaranteed to be secure. These proofs were extended by Wehner and Wullschleger [123] to a simulation-based framework that guarantees sequential composition. Also, in a parallel work, Fehr and Schaffner developed a sequential composability framework under which $\Pi_{\text{bqs}}^{\text{BBCS}}$ is secure considering the BQS model.

The more desirable quantum-UC framework was extended by Unruh and combined with the BQS model [116]. In Unruh's work, he developed the concept of BQS-UC security which, as in UC security, implies a very similar composition theorem. The only difference is that in the BQS-UC framework we have to keep track of the quantum memory-bound used by the machines activated during the protocol. Under this framework, Unruh follows a different approach as he does not use the protocol $\Pi_{\text{bqs}}^{\text{BBCS}}$ (Figure 3.3). He presents a BQS-UC secure commitment protocol and composes it with the $\Pi_{\mathcal{F}_{\text{COM}}}^{\text{BBCS}}$ protocol (Figure 3.2) in order to get a constant-round protocol that BQS-UC-emulates any two-party functionality.

3.2.5 Noisy-quantum-storage model

Notation conflict: \mathcal{F} to denote a CPTP map

The noisy-quantum-storage model, or NQS model for short, is a generalization of the BQS model. In the NQS model, the adversaries are allowed to keep any fraction ν of the transmitted qubits (including the case $\nu = 1$) but their quantum memory is assumed to be noisy [88], i.e. it is impossible to store qubits for some amount of time (Δt) without undergoing decoherence.

More formally, the decoherence process of the qubits in the noisy storage is described by a completely positive trace preserving (CPTP) map (also called channel) $\mathcal{C} : \mathcal{B}(\mathcal{H}_{\text{in}}) \rightarrow \mathcal{B}(\mathcal{H}_{\text{out}})$, where $\mathcal{H}_{\text{in/out}}$ is the Hilbert space of the stored qubits before (in) and after (out)

the storing period Δt and $\mathcal{B}(\mathcal{H})$ is the set of positive semi-definite operators with unitary trace acting on an Hilbert space \mathcal{H} . \mathcal{C} receives a quantum state $\rho \in \mathcal{H}_{\text{in}}$ at time t and outputs a quantum state $\rho' \in \mathcal{H}_{\text{out}}$ at a later time $t + \Delta t$.

With this formulation, we can easily see that the BQS model is a particular case of the NQS. In BQS, the channel is of the form $\mathcal{C} = \mathbb{1}^{\otimes \nu n}$, where the storage rate ν is the fraction of transmitted qubits stored in the quantum memory. The most studied scenario is restricted to n -fold quantum channels, i.e. $\mathcal{C} = \mathcal{N}^{\otimes \nu n}$ [87, 88, 124], where the channel \mathcal{N} is applied independently to each individual stored qubit. In this particular case, it is possible to derive specific security parameters.

Protocols. The protocol from BQS model $\Pi_{\text{bqs}}^{\text{BBCS}}$ is also considered to be secure in the NQS model [124]. However, the first proposed protocol analysed in this general NQS model was developed by König et al. [88]. This protocol draws inspiration from the research line initiated by Cachin, Crépeau and Marcil [125] about classical OT in the bounded-classical-storage model [126, 127]. Similar to these works [125–127], the protocol presented by König et al. [88] uses the following two important techniques in its classical post-processing phase: encoding of sets and interactive hashing. The former is defined as an injective function $\text{Enc} : \{0, 1\}^t \rightarrow \mathcal{T}$, where \mathcal{T} is a set of all subsets of $[n]$ with size $n/4$. The latter is a two-party protocol between Alice and Bob with the following specifications. Bob inputs some message W^t and both parties receive two messages W_0^t and W_1^t such that there exists some $b \in \{0, 1\}$ with $W_b^t = W^t$. The index b is unknown to Alice, and Bob has little control over the choice of the other message W^t , i.e. it is randomly chosen by the functionality.

In this review, we only present the naïve protocol presented in the original paper [88] as it is enough to give an intuition on the protocol. Although both $\Pi_{\text{bqs}}^{\text{BBCS}}$ and $\Pi_{\text{nqs}}^{\text{BBCS}}$ protocols are different, we keep a similar notation for a comparison purpose. The protocol $\Pi_{\text{nqs}}^{\text{BBCS}}$ (Figure 3.4) goes as follows. The first two phases (*BB84* and *Waiting time*) are the same as in $\Pi_{\text{bqs}}^{\text{BBCS}}$ (Figure 3.3). Then, both parties generate a very similar resource to oblivious keys, named *weak string erasure* (WSE). After this WSE process, the sender also holds the totality of the key ok^S , while the receiver holds a fourth of this key, i.e. the tuple $(I, \text{ok}^R := \text{ok}_I^S)$ where I is the set of indexes they measured in the same basis and its size is given by $|I| = \frac{n}{4}$. Then, along with a method of encoding sets into binary strings, both parties use interactive hashing to generate two index subsets, I_0 and I_1 , where the sender plays the role of Alice, and the receiver plays the role of Bob. The two subsets (I_0 and I_1) together with two 2-universal hash functions are enough for the sender to generate her output messages (m_0, m_1) and the receiver to get his bit choice along with the corresponding message (b, m_b) . For more details on the protocols for encodings of sets

and interactive hashing, we refer to Ding et al. [126] and Savvides [127].

Naïve $\Pi_{\text{nqs}}^{\text{BBCS}}$ protocol

Parameters: n , security parameter; \mathcal{F} two-universal family of hash functions.

S input: \perp .

R input: \perp .

BB84 phase: Same as in Π^{BBCS} (Figure 3.1).

Waiting time phase: Same as in $\Pi_{\text{bqs}}^{\text{BBCS}}$ (Figure 3.3).

Weak String Erasure phase: Similar to *Oblivious key phase* of Π^{BBCS} (Figure 3.1).

4. S reveals to R the bases θ^S used during the *BB84 phase* and sets his oblivious key to $\text{ok}^S := \mathbf{x}^S$.
5. R computes $\mathbf{e}^R = \theta^R \oplus \theta^S$. Then, he defines $I = \{i : \mathbf{e}_i^R = 0\}$ and sets $\text{ok}^R := \mathbf{x}_I^R$.
6. If $|I| < n/4$, R randomly adds elements to I and pads the corresponding positions in ok^R with 0s. Otherwise, he randomly truncates I to size $n/4$, and deletes the corresponding values in ok^R .

Interactive hashing phase:

7. S and R execute interactive hashing with R's input W to be equal to a description of $I = \text{Enc}(W)$. They interpret the outputs W_0 and W_1 as descriptions of subsets I_0 and I_1 of $[n]$.

Transfer phase:

5. S generates random $f_0, f_1 \leftarrow_{\$} \mathcal{F}$ and sends them to R.
6. S computes the pair of messages (m_0, m_1) as $m_i = f_i(\text{ok}_{I_i}^S)$.
7. R computes $b \in \{0, 1\}$ by comparing $I = I_b$ and computes $m_b = f_b(\text{ok}_I^R)$.

S output: $(m_0, m_1) \in \{0, 1\}^l$ (two messages).

R output: (b, m_b) where $b \in \{0, 1\}$ (bit choice).

Figure 3.4: BBCS OT protocol in the noisy-quantum-storage model.

Security. Based on the original BQS protocol (Figure 3.3), the first proofs in the NQS model were developed by Schaffner, Wehner and Terhal [87, 128]. However, in these initial

works, the authors only considered individual-storage attacks, where the adversary treats all incoming qubits equally. Subsequently, Schaffner [124] was able to prove the security of $\Pi_{\text{bqs}}^{\text{BBCS}}$ against arbitrary attacks in the more general NQS model defined by König et al. [88].

In this more general NQS model, the security of both protocols $\Pi_{\text{bqs}}^{\text{BBCS}}$ and $\Pi_{\text{nqs}}^{\text{BBCS}}$ (Figures 3.3 and 3.4) against a dishonest receiver depends on the possibility to set a lower-bound on the min-entropy of the “unknown” key $\text{ok}_{I_1-b}^S$ given the receiver’s quantum side information. His quantum side information is given by the output of the quantum channel \mathcal{C} when applied to the received states. More formally, one has to lower-bound the expression $H_{\min}(\text{ok}_{I_1-b}^S | \mathcal{C}(Q_{\text{in}}))$, where Q_{in} denotes the subsystem of the received states before undergoing decoherence. It is proven [88] that this lower-bound depends on the receiver’s maximal success probability of correctly decoding a randomly chosen n -bit string $x \in \{0,1\}^n$ sent over the quantum channel \mathcal{C} , i.e. $P_{\text{succ}}^{\mathcal{C}}(n)$. This result is given by Lemma 1.

Lemma 1 (Lemma II.2. from [88]). *Consider an arbitrary ccq-state ρ_{XTQ} , and let $\varepsilon, \varepsilon' > 0$ be arbitrary. Let $\mathcal{C} : \mathcal{B}(\mathcal{H}_{Q_{\text{in}}}) \rightarrow \mathcal{B}(\mathcal{H}_{Q_{\text{out}}})$ be an arbitrary CPTP map, where $\mathcal{H}_{Q_{\text{in}}}$ and $\mathcal{H}_{Q_{\text{out}}}$ are the Hilbert space corresponding to the subsystem Q_{in} and Q_{out} , respectively. Then,*

$$H_{\min}^{\varepsilon+\varepsilon'}(X | T\mathcal{C}(Q)) \geq -\log P_{\text{succ}}^{\mathcal{C}} \left(\left\lfloor H_{\min}^{\varepsilon}(X | T) - \log \frac{1}{\varepsilon} \right\rfloor \right),$$

where H^{ε} denotes the smooth min-entropy.

For particular channels $\mathcal{C} = \mathcal{N}^{\otimes \nu}$, König et al. [88] concluded that security in the NQS model can be obtained in case

$$\mathcal{C}_{\mathcal{N}} \cdot \nu < \frac{1}{2},$$

where $\mathcal{C}_{\mathcal{N}}$ is the classical capacity of quantum channels \mathcal{N} satisfying a particular property (strong-converse property).

3.2.6 Hacking attacks to QOT

Talk about what I wrote in the paper

Talk about how to mitigate this

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