Cyberattacks on Quantum Networked Computation and Communications – Hacking the Superdense Coding Protocol on IBM's Quantum Computers

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Abstract

The development of automated gate specification for quantum communications and quantum networked computation opens up the way for malware designed at corrupting the automation software, changing the automated quantum communications protocols and algorithms. We study two types of attacks on automated quantum communications protocols and simulate these attacks on the superdense coding protocol, using remote access to IBM's Quantum Computers available through IBM Q Experience to simulate these attacks on what would be a low noise quantum communications network. The first type of attack leads to a hackercontrolled bijective transformation of the final measured strings, the second type of attack is a unitary scrambling attack that modifies the automated gate specification to effectively scramble the final measurement, disrupting quantum communications and taking advantage of quantum randomness upon measurement in a way that makes it difficult to distinguish from hardware malfunction or from a sudden rise in environmental noise. We show that, due to quantum entanglement and symmetries, the second type of attack works as a way to strategically disrupt quantum communications networks and quantum networked computation in a way that makes it difficult to ascertain which node was attacked. The main findings are discussed in the wider setting of quantum cybersecurity and quantum networked computation, where ways of hacking including the role of insider threats are discussed.

Ketwords: Quantum Networked Computation, Quantum Internet, Quantum Cybersecurity, Entanglement, Symmetry, Automated Quantum Communications, Superdense Coding, IBM Q Experience, Intelligence Studies, Strategic Studies

1 Introduction

The current interface with quantum computing resources mainly relies on a cloud-based access to quantum computing, one can design quantum algorithms and see the drawing of the circuits on a computer screen or look at some implementation of this code in some programming language, a good example of this type of interface is IBM's Quantum Experience (IBM Q Experience), which uses a visual circuit design operating with Open Quantum Assembly Language (OpenQASM) and Qiskit, which allows one to use the Python programming language for implementing quantum algorithms that can be run through cloud-based access to quantum computers, including the simulation of quantum metworked computation, quantum communications and, even, quantum machine learning (Cross et al., 2017; Cross, 2018; Gonçalves, 2019).

With the development of quantum computation and communications, cloudbased access to quantum servers and an access to quantum communications and computational networks, combining elements of a classical internet and a quantum internet, may become increasingly feasible (Gonçalves, 2017, 2019), furthermore, the development of quantum communications and remote access to quantum computation will demand some level of automation of communications' protocols and of computation networks, where a classical level user interaction with quantum technologies will tend to involve a standard high-level user interface, under which that user's interaction and commands are automatically encoded into quantum machine language, without the user having to think about the machine language implementation or even know quantum computation.

Such an infrastructure demands an automated translation of a user's interaction patterns and intended actions into qubits and relevant quantum circuits, as well as the automation of quantum communications protocols and algorithms, which raises the possibility of malware that can take advantage and disrupt the automated translation of high-level interactions into quantum machine language, effectively disrupting the interaction with quantum devices and quantum communications. This software-level hacking, which draws upon the fact that such communications' protocols involve automated quantum networked computation that demands appropriate software tools to automatically implement the correct computations at each network node for the communications protocols to function, is what we consider here, within the context of quantum cybersecurity.

The research field of quantum cybersecurity, within the context of Strategic Studies, includes the assessment of the strategic advantage coming from quantum networked computation in terms of cyberdefense, cryptographic solutions and information dominance (Mailloux et al., 2016a,b; Gonçalves, 2017, 2019; Abellan and Pruneri, 2018; Gompert and Libicki, 2021), it also addresses cybersecurity threats coming from quantum computers as well as the cybersecurity threats to quantum networks including attacks on quantum repeaters and quantum key distribution (QKD) (Wu and Lidar, 2006; Larsson, 2002; Lydersen et al., 2010; Gerhardt et al., 2011; Jogenfors et al., 2015; Mailloux et al., 2016b, Hughes-Salas et al., 2018; Makarov and Hjelme, 2005; Satoh et al., 2018, 2020).

Indeed, QKD has been shown to be vulnerable to Distributed Denial of Service (DDoS) attacks (Schartner and Rass, 2010) that disrupt key generation, proposals to reduce this vulnerability include quantum-secured paths over a network configuration, Hughes-Salas et al. (2018), for instance, proposed a DDoS mitigation over a QKD network using software defined networking (SDN), testing experimentally not only the vulnerability of QKD to DDoS attacks but also the role of an SDN application for mitigating these attacks.

While eavesdropping on quantum communications is an important goal for hackers, other types of cyberattacks on quantum computers and communications are possible for which a hacker's intention is not to eavesdrop but rather to disrupt quantum networked computation and quantum communications (Wu and Lidar, 2006).

In a setting where quantum communications protocols can be automated, using software for automatically translating high-level interface interactions into sequences of unitary gates to be implemented at different nodes of a quantum communications network, the possibility of an attack to disrupt common quantum communications protocols becomes feasible, such that the software that was used to automate a given network node's quantum computations on received qubits can be changed by malware installed either remotely or by way of an insider, such a malware can change the software code so that the main automated communications protocol no longer runs the protocol's quantum networked computational circuit but, instead, runs a different (hacked) circuit, in this way, the automated communications protocol is disrupted, it is this scenario that we deal with in the present work.

These types of attacks fall in the same typology of DDoS in terms of pattern, in the sense that their strategic goal is to disrupt networked computation and communications during a period of time, for a strategic or tactical advantage, these types of attacks are not aimed at eavesdropping, nor, like DDoS, are they supposed to be hidden, in the sense that the attacked parties know or may quickly find out that they are being attacked, but the problem of finding which network node was attacked becomes more difficult due to the use of entanglement and symmetries in quantum communications, which allows hackers to hide the attacked nodes and qubits, a point that we will address in the studied examples.

Like a classical computer virus that can corrupt a system's function, malware targeting automation of quantum communications and networked computation protocols may become the next frontier in hacking when faced with a sufficiently advanced quantum computational and communicational infrastructure, where automation for translation of high-level commands to quantum machine language is hacked.

Under this context, if a quantum communications protocol has been hacked with installed malware this may lead to a corruption of the interaction with the networked quantum computational and communicational infrastructure. From a hacker's standpoint, this is not about eavesdropping on a quantum communications channel, as stated above, but rather about installing malware that can disrupt quantum communications. In the current article, we deal with this framework, such that the hacking is assumed to be done by replacement of code for automated gate specification in automated communications protocols. We analyze different attack patterns to a well-known quantum communications protocol: quantum superdense coding.

We assume, as stated, an automated setting where the users do not directly access the quantum gates but, instead, operate on a high-level classical user interface, such that the whole translation of the classical message to the quantum framework is done automatically. In this setting, a hacker can attack different nodes in the communications network in order to change the sent message without eavesdropping on the circuit, leading to a bijective recoding of the message to be sent, this is the first type of attack to the superdense coding protocol that we address here, we call it a bijection attack.

Bijection attacks can take longer to detect, unless there is communication between Alice and Bob with test qubits sent to evaluate whether or not the communication circuit has been hacked or if there is a disruption coming from post-processing automation that relies on the protocol's output qubits. Bijection attacks are easier to deal with, in that one can effectively invert the bijection to recover the original message, quarantining the malware and giving enough time for a quantum cybersecurity team to find the malware and remove it.

A second type of attack that we research is the purposeful scrambling of the communications network, introducing specific unitary gates that lead to a random output for the circuit at the measurement endpoint. This second type of attack, which also uses unitary gates, randomizes the final decoded message, taking advantage of quantum randomness upon measurement, the main goal of the hacker is, again, not to eavesdrop but rather to scramble the decoded message at the end of the communications protocol when measurement takes place, this attack is not meant to be hidden, it becomes a quantum variant of a DDoS attack, in the sense that it makes the network's quantum computational and communicational operativity useless, being difficult to distinguish from a hardware malfunction or an environmental increase in noise.

We also show that, due to entanglement and symmetries, the hacker can produce random results, upon measurement, on a final communications' node where qubits are measured, by attacking another node and changing other qubits in a communications network. In a context of automated communications protocols, where users have a high-level classical interface with the communications infrastructure, it is up to quantum cybersecurity to find the nodes and qubits that were hacked, but entanglement and symmetries become a problem in the sense that the same end-result can occur by attacking different nodes and qubits with different quantum unitary gates, which demands, on the part of quantum cybersecurity, a checking of different elements in a quantum communications network.

As stated, this attack cannot be easily quarantined in the way the previous one was, especially since different unitary gates applied to different nodes and qubits can, as we will show, lead to the same end result, for instance, the hacker can attack one node and one qubit with the noise-like results occurring at another node and for a different qubit, this places an added pressure on quantum cybersecurity forensics to find the attacked networked node and remove the malware. While, in the case of the simpler quantum superdense coding protocol, this checking is easier to do, since we have three nodes that can be hacked (the entanglement source, Alice's system and Bob's system), for larger communications networks, the number of nodes that need to be checked for malware rises. Scrambling attacks can, therefore, become just as damaging as a DDoS attack.

The work is divided into two sections, in section 2, we review the superdense coding protocol (subsection 2.1), then we address the bijection attacks (subsection 2.2) and the scrambling attacks (subsection 2.3), simulating these attacks on IBM's quantum computers, in section 3, we present a final discussion on the implications for quantum cybersecurity and the demand for the development of quantum cybersecurity forensics as a research field that can study how quantum cyberattacks aimed at disrupting quantum communications and quantum computation can be implemented, as well as how to find methods for detection, protection and elimination of quantum malware.

On this regard, there is an intersection with Intelligence Studies, in that a main way for implementing the types of attacks that we are considering, at least in the foreseeable future, comes from using human intelligence (HUMINT) in the form of an infiltrated agent, or compromised employee in a target organization, in order to find vulnerabilities and install the malware to disrupt the automated protocols, in this way, stronger cybersecurity countermeasures linked to insider threat are needed in order to protect quantum networked computation from disruption. This is a critical subject matter for countries' National Intelligence and Security since, as distributed quantum computation and a hybrid of quantum and classical internet is developed, Universities, Corporations, Banks, Governments, Armed Forces and Intelligence Agencies will be at the forefront as targets for maneuvers based on HUMINT aimed at disrupting quantum communications protocols.

2 Hacking Superdense Coding

2.1 Superdense Coding

The superdense coding protocol uses entanglement, symmetry and quantum interference to allow Alice to communicate a two classical bits message to Bob, sending only one qubit (Zygelman, 2018). In the framework that we are considering, there is an automated source that entangles two qubits and sends one to Alice's automated system and another one to Bob's automated system, so that Alice and Bob's respective systems share a symmetric Bell pair of the type:

$$|\text{Bob}+\text{Alice}\rangle = \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$
 (1)

Then Alice's system, as per the protocol, performs automatically a series of computations on the qubit it received from the entanglement source, depending on the message to be sent, these computations follow the automated superdense coding protocol, after these computations, Alice's system sends the transformed qubit to Bob's system which automatically applies a CNOT gate on the qubit it received from the entanglement source using the qubit it received from the Alice's system as the control qubit, after this CNOT gate, Bob's system performs a Hadamard transform on Alice's qubit and then measures both qubits to extract the final bit string, which is decoded and shown to Bob as a high-level message.

As discussed in the introduction, we consider here a context of quantum communications where the users operate on a high-level interface, with the quantum gates being automatically implemented in the background by software without the users accessing them, that is, we are considering a framework where quantum computation and quantum communications have become sufficiently developed so that there is an automation of the translation of high-level instructions to the (quantum) machine language, so that Alice just types in the message, in the case of superdense coding one of four possible messages that she wants to send Bob, which is then translated into one of four corresponding sequences of quantum operations that will lead to the desired result under the established automated superdense coding communications protocol.

In the context of superdense coding, Alice can send one of four alternative messages to Bob, encoded in the machine language by a two bits string or, under repeated use of the quatum communications network, longer messages represented by longer strings. To keep things general, we are not addressing the specific messages that Alice may be sending, therefore, we just assume that Alice sends one of four messages, and that the system automatically differentiates between one of those four messages using the classical bit strings in the set {00,01,10,11}, the translation on Bob's end from these bit strings to actual high-level messages is not also being addressed here, we will however discuss the issue of the uncovering of the hack, if that hack occurs, which will demand, on the part of a quatum cybersecurity forensics team, to look at the systems' automation software for installed malware.

Considering the standard superdense coding without the hack, in the general scenario under analysis, the adaptive quantum circuit composition is fully automated and is like a black box for both Alice and Bob, who are, in this scenario, like standard users that know nothing about the actual workings of quantum computation nor do they care about it, all they know is how to interact with the high-level interface not looking "under the hood".

The above is a very important point, we are assuming an advanced stage of automation and integration of cyber-physical systems with quantum communications' infrastructures, in such a way that the people in the communication circuit are not quantum experts and the whole quantum infrastructure works in the background. This will be key to illustrate the dangers and effectiveness of quantum malware on a standard quantum communications protocol, since Alice and Bob may think that their automated systems are working and it may take a while for them to realize that something is wrong, which can typically occur if Alice sends one of four messages repeatedly or, alternatively, if the protocol is used multiple times to send longer messages. Let us address, first, the process for each pattern without the malware, thus reviewing the standard superdense coding protocol and, afterwards, discuss how Eve can disrupt the communications circuit with a unitary gate attack without eavesdropping. Figure 1 shows the four circuits used for the standard superdense coding, the code in each case is divided into three sections, the first is the entanglement source section, the second is Alice's system's automated operations section and the third is Bob's system's automated operations.



Figure 1: Superdense coding circuits, for sending: (a) 00, (b) 01, (c) 10, (d) 11.

It should be stressed that we are using the same convention in terms of notation as IBM's, in order to make it easier to compare with the experimental implementation, in this notation, when reading from left to right, Alice's register comes second while Bob's comes first so that the string is read q_1q_0 , which leads, for the strings 01 and 10, to a replacement of the stantard protocol's circuits, for which the notation is the reverse q_0q_1 (Zygelman, 2018).

In each case, if Alice types in the message that is represented by a string xy, with $x, y \in \{0, 1\}$, then, the automated quantum communications system applies the necessary computations on Alice's qubit and then sends it to Bob, whose system automatically applies a CNOT gate followed by a Hadamard transform, measures the two qubits, extracts the corresponding measured string and translates the message from machine language (string of two bits) into natural language, showing Alice's high-level message to Bob.

The following table shows the simulation of the above four circuits on IBM's quantum computer ibmqx2.

Observed String	Intended String			
	00	01	10	11
00	91.7%	9.3%	5.7%	0.8%
01	1.3%	84.6%	1.5%	5.1%
10	5.9%	1.4%	89.7%	7.9%
11	1.1%	4.7%	3.1%	86.2%

Table 1: Simulation of figure 1's superdense coding protocol on the ibmqx2 quantum device, with 1000 runs used for each experiment.

We can see that the simulation on an actual quantum computer contains some noise, but the intended result holds for the various circuits with a more than 80% frequency. The above results constitute a review and an experimental trial of the superdense coding protocol on IBM's quantum devices, which can, in this case, be used as simulators of low-noise quantum communications networks.

Let, now, \hat{C}_{xy} , with $x, y \in \{0, 1\}$, denote the sequence of operations for the non-hacked superdense coding, including the entanglement source operations, followed by Alice's system's automated operations and then by Bob's system's automated operations, leading to the final string xy, so that $\hat{C}_{xy} |00\rangle = |xy\rangle$.

Malware that changes the automated gate definition, will change the code for the protocol at one or more of the nodes in the communications network such that the chains \hat{C}_{xy} are replaced by corresponding hacked chains \hat{C}_{xy}^{Hacked} , which can have one or more additional unitary operators applied by the automated protocol at one or more compromised systems.

Bijection attacks, the first type of cyberattacks that we consider, change the automated gate sequence definition software, so that if xy is the original correct string for the superdense coding protocol, then we get the recoding:

$$\hat{C}_{xy}^{Hacked} \left| 00 \right\rangle = e^{i\phi_{xy}} \left| f(xy) \right\rangle \tag{2}$$

where the function $f: \{00, 01, 10, 11\} \rightarrow \{00, 01, 10, 11\}$ is a bijection and ϕ_{xy} is an arbitrary phase. Considering the above equation, it follows that the bijection attacks lead to a bijective mapping of the projector set $\{|xy\rangle \langle xy| : x, y = 0, 1\}$ onto itself, this is due to the fact that the global phase present in the state vectors disappears for each transformed density under \hat{C}_{xy}^{Hacked} , so that, given a hacked protocol \hat{C}_{xy}^{Hacked} there is a whole family of equivalent hacks all consistent with the same bijection f but that only differ by a U(1) group transformation, this is an important symmetry for this type of cyberattack.

The second type of attack that we consider uses unitary gates for scrambling the measurement results, which means that instead of a computation of a bijective mapping on the main computational basis' projector set, we get, for each activation of the protocol for a string xy, a superposition state of the form:

$$\hat{C}_{xy}^{Hacked} \left| 00 \right\rangle = \sum_{w,z \in \{0,1\}} \psi_{xy}(wz) \left| wz \right\rangle \tag{3}$$

Upon measurement, Bob's system will get a random output with probabilities given by the squared amplitudes $|\psi_{xy}(wz)|^2$, this also means that the correct output for the superdense coding will occur with a probability of $|\psi_{xy}(xy)|^2$.

Bijection and unitary scrambling attacks can be uncovered with multiple uses of the protocol using repeated pre-established test messages, or when sending of longer strings or, even, under a direct communication between Alice and Bob which may allow the users to detect a mismatching between intended messages and received messages. However, in noisy channels (even with low noise) this randomness may be difficult to distinguish from a quantum hardware malfunction or strong environmental noise fluctuations that may have corrupted the communications network. We now address these two types of attacks, starting with bijection attacks.

2.2 Bijection Attacks

To illustrate bijection attacks, let us assume that Eve has managed to get malware installed on Alice's system so that the automated superdense coding protocol is modified, another possibility would be to attack Bob's system or even the entanglement source, for the sake of illustration of bijection attack profiles, we focus first on Alice's system and proceed from there to address other target nodes.

Now, in this first example, Eve's malware interferes with Alice's automated coding software, without Alice knowing that she has been hacked. Under Eve's malware, a quantum unitary gate or a sequence of unitary gates are, in this case, applied to Alice's protocol each time it is used, independently of the typed message, so that no eavesdropping is needed.

We will be considering here the effect of elementary gates in disrupting superdense coding, so that we will be working, for now, with a single gate operation. Since the hack takes the form of a single unitary gate, Eve is not eavesdropping on Alice and Bob, as stated before, indeed, the automated quantum operation introduced by the malware is the same whatever the sequence of gates implemented on Alice's side, the protocol is, in this way, disrupted without Eve having to eavesdrop on Alice and Bob.

There are several possible unitary gate insertion versions, where the malware can operate to change Alice system's software-defined computational circuit. In the case of quantum communications protocols, where the software automatically changes the circuit in accordance with the message being sent, as is the case that we are addressing, it is easier for the malware to either operate at the beginning or at the end of a system's computational chain, that is, at the beginning or at the end of the computing system's automated operations, in this case, the superdense coding protocol operates normally but there is either an additional final operation, always the same, that transforms the qubit being sent, or an initial operation that changes the qubit before employing Alice's automated operations.

Whether operating at the end or at the beginning, since the operations are the same, Eve is able to disrupt the superdense coding without having to eavesdrop on it, therefore, independently of the message sent by Alice. Figure 2 exemplifies the circuits with an X gate malware attack on the quantum circuit, where the gate always operates at the end of Alice's system's quantum computations, while figure 3 shows the operation of the malware at the beginning of Alice system's computations, both figures illustrate how the hack works for each of the alternative automated gate sequences that characterize the superdense coding communications protocol.



Figure 2: Hacked superdense coding circuits with X gate at the end of Alice's system's computational chain.



Figure 3: Hacked superdense coding circuits with X gate at the beginning of Alice system's computational chain.

In table 2, we show the results on the final state vectors from figures 2 and 3's hacked circuits, for the noise-free communications network. As is visible

from the table, the hack works so that in each case the final state vector differs from the superdense coding intended result. From the state vectors shown in table 2, assuming a noiseless communications network, the final measured string when the X gate is automatically applied at the beginning of Alice's system's automated operations will coincide with the measured string when the gate is applied at the end, since each final state vector with the gate applied at the beginning coincides with the state vector with the gate applied at the end, except in two cases where there is a global negative phase difference, which does not affect the final quantum measurement.

Intended String	Final state vector	Final state vector
	with X gate at the	with X gate at the
	end of Alice's chain	beginning of
		Alice's chain
00	$ 10\rangle$	$ 10\rangle$
01	$ $ $- 11\rangle$	$ 11\rangle$
10	$ 00\rangle$	$ 00\rangle$
11	$- 01\rangle$	$ 01\rangle$

Table 2: Final state vectors resulting from the X gate malware at the beginning and at the end of Alice's system's computational chain.

In the ideal noiseless quantum communications context, through her hack of Alice's computational chain, Eve is capable of rotating the final output state vector so that Bob's system always measures the wrong final string.

From these results, it follows that if we work with the final output density operator at the end of the protocol, we find that the X gate attack, whether at the beginning or the end of Alice's circuit, leads to the same remapping of the basis densities that is one-to-one and onto, therefore, bijective.

The reason why the final density with the malware is the same whether the X gate is applied at the beginning or at the end of Alice's system's operations is due to the fact that the final state vectors, with the malware, only differ by a global phase when the X gate is applied, we, thus, have an invariance for the final hacked densities with respect to the placement of the X gate at the beginning or at the end of Alice's computational chain, since the final state vectors only differ by a global phase, which means that, working with the final densities, we get the same bijection for the measurement results, since the projector set is the same.

This is an important hacking symmetry, furthermore, Eve can change Bob's measurement, obtaining the same results in terms of bijective modification by:

- 1. Hacking Alice's system with the X gate applied to Alice's qubit at the beginning of Alice's chain;
- 2. Hacking Alice's system with the X gate applied to Alice's qubit at the end of Alice's chain;

- 3. Hacking the entanglement source with the X gate applied to Alice's qubit at the end of the entanglement source's operations;
- 4. Hacking Bob's system with the X gate applied to Alice's qubit, before the final CNOT and Hadamard transform.

In an ideal noiseless quantum communications network, the alternatives 1 and 3 lead to the same final state vectors, the same is true for the alternatives 2 and 4, now still taking advantage of quantum symmetries, Eve can also obtain the similar results by hacking Bob's qubit instead of Alice's. For instance, if Eve employs an X gate at the end of the entanglement source's operations on Bob's qubit instead of Alice's, then, Eve obtains the same resulting state vectors as those that hold for the X gate attack on Alice's qubit at the beginning of Alice's standard superdense coding computational chain, this is due to symmetry and entanglement, namely, the input for Alice's standard superdense coding computations, indeed, after entanglement, hacking Alice's qubit, after the two qubit's are entangled in accordance with equation (1)'s symmetric pattern, we get the Bell state which is fed as (hacked) input for Alice and Bob's standard superdense coding automated operations:

$$\frac{0\rangle \otimes X \left| 0 \right\rangle + \left| 1 \right\rangle \otimes X \left| 1 \right\rangle}{\sqrt{2}} = \frac{\left| 01 \right\rangle + \left| 10 \right\rangle}{\sqrt{2}} \tag{4}$$

This result holds for the two above discussed hacking alternatives 1 and 3. Now, if Eve is able to insert her malware at the entanglement source so that, after the source entangled the two qubits in accordance with the symmetric Bell state in equation (1), and if this malware attacks Bob's qubit with an X gate, then, we get the same hacked input to the remaining superdense coding protocol's operations as in equation (4), indeed:

$$\frac{X|0\rangle \otimes |0\rangle + X|1\rangle \otimes |1\rangle}{\sqrt{2}} = \frac{|10\rangle + |01\rangle}{\sqrt{2}} = \frac{|01\rangle + |10\rangle}{\sqrt{2}}$$
(5)

Therefore, Eve can get the same final hacking results by attacking different systems and qubits, taking a strategic advantage of quantum entanglement and symmetry.

Another example of bijection attack using a different operator is the Z gate attack. In this case, instead of applying an X gate, Eve's malware introduces a Z gate at the beginning or at the end of Alice's chain. Table 3 shows the results of the Z gate attack on the final state vectors, which again coincide up to a global phase.

Intended String	Final state vector	Final state vector
	with Z gate at the	with Z gate at the
	end of Alice's chain	beginning of
		Alice's chain
00	01	01
00		
01	$ 00\rangle$	$ 00\rangle$
10	$ 11\rangle$	$ - 11\rangle$
11	$ 10\rangle$	$ - 10\rangle$

Table 3: Final state vectors resulting from the Z gate malware at the beginning and at the end of Alice's system's computational chain.

These two malware attacks are examples of the general class of bijection attacks that remap the algorithm's final densities with a one-to-one and onto transformation defined on the projector set $\{|xy\rangle \langle xy| : x, y = 0, 1\}$. Eve's intention, in this case, is to change the final message in a specific way, so that, in the noiseless communications circuit, the final measured string will be different from Alice's intended message.

Now, since these attacks lead to a deterministic invertible remapping of the intended two bits string onto another two bits string, the one-to-one and onto nature of this remapping is a weakeness for a long-term hack, which means that this can only work as a short-term attack aimed at fooling Alice and Bob's communications for a short period, in order to disrupt communications. It introduces a form of man-in-the-middle variant where Eve replaces Alice's messages in a specific way, and Bob is fooled into believing that he is receiving Alice's true message while he is in fact receiving Eve's altered messages.

If Alice and Bob communicate or use a changing preestablished test message, each time they use the system, then the hack can be uncovered. However, the test message solution can be overturned depending on the way it is built, for instance, automated test messages if hacked as well can lead to a longer period until the hack is found, unless Alice and Bob communicated directly or use multiple communication channels.

Bijection attacks can also be useful if the context is not one of message reading by Bob, but rather one in which we are dealing with distributed automated networked quantum computation, such that Alice's system provides an initial state for Bob's system to perform aditional automated computations on the final outputs coming from the communications network, in this context, Eve's malware will alter Bob's further computations in a controlled way. In this case, the malware can also take a while longer to be uncovered, depending on the additional computations performed on the outputs coming from the communications network.

In either case, the above results show a vulnerability of the quantum superdense coding protocol to bijection attacks. However, once uncovered, bijection attacks are easy to counter, one can produce a form of quantum quarantine of the malware, by remapping on Bob's end the final densities through a unitary rotation that restores the original protocol, leaving the cybersecurity team ample time to check the network nodes for the malware. During quarantine, one can even fool Eve into believing that her attack has not been countered.

Now, while with bijection attacks, Eve wishes to change the measured output in a controlled way, scrambling attacks are different since their strategic goal is to use unitary gates to produce a random result upon measurement, taking advantage of quantum randomness upon measurement, damaging quantum communications, this quantum communications scrambling attack through unitary gates becomes more difficult to distinguish from a communications circuit corrupted by environmental noise, even though the scrambling attack is unitary. If a quantum communications circuit has some noise, even if small, then, the cyberattack may increase the circuit's random output, furthermore, this type of malware is not as easily quarantined as the previous one.

We will now address examples of unitary scrambling attacks on the quantum superdense coding and how entanglement and symmetries can be used to hide the attacked system, thus becoming strategic key drivers for quantum cyberoperations.

2.3 Unitary Scrambling Attacks

Unitary scrambling attacks employ malware to corrupt automatic gate encoding and take advantage of quantum randomness at the level of the final measurement in order to disrupt a quantum communications protocol, masking the cyberattack under the cover of quantum environmental noise corruption or a quantum hardware malfunction, when, in fact, the error level of the quantum communications circuit with respect to the intended output was increased not due to external noise but rather through a unitary gate that produced a quantum superposition with amplitudes that lead to significant deviations, upon measurement, from a final intended output, taking advantage of the usual quantum randomness upon measurement to give the appearance of rise in communications channel noise, such that, unaware that the communications network has been hacked, the participants will get random fluctuations in the measurement outputs in a way that will no longer match the communications protocol.

In this case, Eve's hidding of the attack can only be short lived in the sense that it may not take a long time to find out that something is wrong with the communications network, Eve's intention here is similar to a DDoS attack, since her endgame is to disrupt the communications protocol by producing random measurement results for one or more qubits, the effectiveness of this attack is enhanced by a few points: on the one hand, such an attack can be difficult to distinguish from a hardware malfunction, or environmental noise increase in a noisy communications network, which may lead to an additional cost from the part of systems' maintenance to identify the source of output error, on the other hand, as we will show, by taking advantage of entanglement and symmetries involved in a quantum communications protocol, a hacker can attack one system and one qubit but produce a disruption on another qubit that never passed through a hacked system, this hacking propagation makes it more difficult to uncover which system and qubits were actually hacked.

Once a disruption takes place, quantum cybersecurity teams in collaboration with system's maintenance will have to identify the disrupted node and check for hardware malfunction or actual malware operating at the level of the automated gate translation.

An example of such a software attack profile, for the superdense coding protocol, can be obtained through an S gate attack on Alice's system, this is when Eve installs malware in Alice's automated gate specification introducing an additional S gate operating either at the end or at the beginning of Alice's operator chain, for both these cases, as shown in table 4, the attack produces, at the end of the superdense coding protocol, a superposition at the level of Alice's qubit, while leaving Bob's qubit in the correct superdense coding protocol's configuration.

Intended String	Final state vector with S	Final state vector with S
	gate at the end of Alice's	gate at the beginning of
	chain	Alice's chain
00	$ 0 angle \otimes rac{(1+i) 0 angle + (1-i) 1 angle}{2}$	$ 0 angle \otimes rac{(1+i) 0 angle + (1-i) 1 angle}{2}$
01	$ 0 angle \otimes rac{(1-i) 0 angle + (1+i) 1 angle}{2}$	$ 0\rangle \otimes \frac{(1-i) 0\rangle + (1+i) 1\rangle}{2}$
10	$ 1 angle \otimes rac{(1+i) 0 angle + (1-i) 1 angle}{2}$	$ 1 angle\otimesrac{(1+i) 0 angle-(1-i) 1 angle}{2}$
11	$ 1\rangle \otimes \frac{(1-i) 0\rangle + (1+i) 1\rangle}{2}$	$ 1\rangle \otimes \frac{-(1-i) 0\rangle + (1+i) 1\rangle}{2}$

Table 4: Final state vectors resulting from the S gate attack at the beginning and at the end of Alice's computational chain.

Table 5 shows the results from the simulation of the hacked protocol on the ibmqx2 device resulting from the S gate applied at the beginning of Alice's chain.

Observed String	Intended String			
Observed String	00	01	10	11
00	45.4%	47.8%	5.7%	6.5%
01	49.5%	46.6%	5.4%	5.6%
10	3.3%	2.7%	40.7%	44.4%
11	1.8%	2.9%	48.2%	43.5%

Table 5: Simulation of the hacked protocol on ibmqx2, with the S gate operating at the beginning of Alice's computational chain. In each case, 1000 runs were used.

The simulations on the ibmqx2 device, which is a low noise quantum computer, helps to simulate the results from implementing the protocol on what would be a low noise quantum communications network, in this case, as shown in table 5, while the final measurement shows that Bob's qubit is in the correct configuration for most of the runs of the protocol (94.9% for the message 00, 94.4% for the message 01, 88.9% for the message 10 and 87.9% for the message 11), Alice's qubit shows a large deviation from the protocol's intended output.

Since only the final measurement results are observable for the users, what the users will see, if they test the circuit with multiple test messages, is a rise in the error rate of Alice's qubit, indeed, in the example of table 5's simulations, in the case of the intended string 00, Alice's qubit was measured with the correct output for 48.7% of the runs, while in the case of the intended string 01, it was measured with the correct output for 49.5% of the runs, for the intended string 10, in turn, we get the correct output in 46.4% of the runs and, finally, for the intended string 11, we get the correct output in 49.1% of the runs.

Considering the intended non-hacked protocol's outputs, table 6 shows the error rates for each qubit with respect to the superdense coding intended outputs, these results from simulating the hacked protocol on ibmqx2 help illustrate what would be the consequences of hacking a low noise quantum communications network, which will be useful in the forensic considerations that we now address.

Intended String	Error rate for	Error rate for
	Alice's qubit	Bob's qubit
00	51.3%	5.1%
01	50.5%	5.6%
10	53.6%	11.1%
11	50.9%	12.1%

Table 6: Error rates between the measured string and the superdense coding intended outputs, obtained from table 5's experimental frequencies.

In tables 5 and 6's simulations, the error rate for Bob is within the boundaries of standard random fluctuations in what would be a low noise quantum communications network, with the minimum error rate for Bob being of 5.1% and the maximum error rate being of 12.1%, however, for Alice, we get the increase in the error rate to a minimum level of 50.5% and a maximum level of 53.6%. From a quantum cybersecurity forensics standpoint this would be a warning signal on possible hardware malfunction, a strong environmental disruption or, alternatively, a cyberattack aimed at disrupting Alice's qubit.

Since the disrupted qubit is Alice's, in the case of a quantum cybersecurity investigation on a possible software hacking of automated gate definition, in the context of a unitary scrambling attack, the investigation might be led to infer a possible hacking targeting directly Alice's qubit, with the probable attack node having been Alice's software for the superdense coding protocol's automation, however, this inference does not necessarily hold for a quantum cybersecurity context as we now show.

In the context of quantum communications hacking, by taking strategic advantage of a non-hacked protocol's employment of entanglement and symmetry, a hacker may be able to disrupt a specific qubit that has been sent through and processed by a specific (sub)network by hacking another entangled qubit that has followed another route of nodes, in this case, even if the two qubits follow separate paths, because they are entangled, a hacker can change one qubit by attacking another qubit along its quantum processing route in the communications network. This characteristic of quantum communications, which incorporates quantum networked computation, makes it more difficult for quantum cybersecurity forensics to find the attacked nodes and qubits, especially in large quantum communications networks.

In our example, the network is small containing only three nodes: the entanglement source, Alice's system and Bob's system, however, as we now show, Alice's qubit can be disrupted with a similar pattern as that of tables 4 to 6 by operating on Bob's qubit at the entanglement source or at Bob's system.

Let us, first, consider the scenario in which Eve is able to insert the malware at the entanglement source with an S gate attack on Bob's qubit where the S gate operates at the end of the entanglement source's superdense coding computational chain and before the qubit is sent to Bob. In table 7, we show the results from simulating this attack on the ibmqx2 quantum device, these results show a very similar profile to that of table 5, indeed, the error with respect to the non-hacked superdense coding protocol's output is raised for Alice's qubit rather than Bob's, even though, this time, Eve's malware led to the modified circuit to operate solely on Bob's qubit.

Observed String	Intended String			
Observed String	00	01	10	11
00	41.1%	47.6%	6.0%	5.6%
01	50.6%	45.0%	7.8%	8.5%
10	4.5%	2.0%	41.4%	40.8%
11	3.8%	5.4%	44.8%	45.1%

Table 7: Simulation of the hacked protocol on ibmqx2, with the S gate operating on Bob's qubit at the end of the entanglement source's computational chain. In each case, 1000 runs were used.

In table 8, we show the error rates with respect to the superdense coding protocol for each qubit, which reinforces the above results, showing that even though Eve's malware operated on Bob's qubit, it was Alice's qubit that was "scrambled".

Intended String	Error rate for	Error rate for
	Alice's qubit	Bob's qubit
00	54.4%	8.3%
01	49.6%	7.4%
10	52.6%	13.8%
11	46.4%	14.1%

Table 8: Error rates between the measured string and the superdense coding intended outputs, obtained for table 7's experimental frequencies.

There is a reason for the results to be similar, indeed, the final state vectors from an S gate attack on Bob's qubit at the end of the entanglement source's operations coincide with the final state vectors for an S gate attack on Alice's qubit at the beginning of Alice's operator chain. These results are specific to quantum communications, and they are linked to entanglement and symmetry, namely, the non-hacked entanglement source's operations have the following structure:

$$\hat{C}_{Ent} = (I \otimes |0\rangle \langle 0| + X \otimes |1\rangle \langle 1|) (I \otimes H)$$
(6)

Considering the initial state $|00\rangle$, we get equation (1)'s symmetric Bell state for Bob and Alice:

$$\hat{C}_{Ent} \left| 00 \right\rangle = \frac{\left| 00 \right\rangle + \left| 11 \right\rangle}{\sqrt{2}} \tag{7}$$

Now, the second qubit is sent to Alice while the first is sent to Bob. In the case where Alice's system is hacked with an S gate applied at the beginning of the superdense coding operations for Alice, the state vector after the hack and before Alice's standard superdense coding operations becomes:

$$\frac{0\rangle \otimes S \left|0\right\rangle + \left|1\right\rangle \otimes S \left|1\right\rangle}{\sqrt{2}} = \frac{\left|00\right\rangle + i \left|11\right\rangle}{\sqrt{2}} \tag{8}$$

In this way, because Alice and Bob's qubits are entangled, the S gate attack has changed the entangled state before running the standard superdense coding protocol's operations for Alice, adding a phase to the branch $|11\rangle$.

On the other hand, if, instead of attacking Alice's qubit, the hack is on Bob's but at the end of the entanglement source's operations, then, the hacked entanglement source's computational chain is given by:

$$\hat{C}_{Ent}^{Hacked} = (S \otimes I) \,\hat{C}_{Ent} \tag{9}$$

Which leads to the following entanglement pattern at the end of the entanglement source's computations:

$$\hat{C}_{Ent}^{Hacked} \left| 00 \right\rangle = \frac{S \left| 0 \right\rangle \otimes \left| 0 \right\rangle + S \left| 1 \right\rangle \otimes \left| 1 \right\rangle}{\sqrt{2}} = \frac{\left| 00 \right\rangle + i \left| 11 \right\rangle}{\sqrt{2}} \tag{10}$$

This is the same output that is obtained when Eve attacks Alice's qubit, instead of Bob's, since the remaining operations coincide for both hacks, when Eve hacks Bob's qubit at the end of the entanglement source with an S gate attack she gets the same state vectors before Alice's standard superdense coding operations than when she hacks Alice's system adding the S gate at the beginning of Alice's system's standard superdense coding operations, this is due to the symmetry of the Bell state that results from the entanglement source's operations.

Now, one might be led to infer that an attack on Bob's qubit leading to a scrambling of Alice's qubit, instead of Bob's could only come from a hack at the entanglement source, however, this is not the case, indeed, Eve can attack Bob's qubit with the scrambling occurring for Alice's qubit by hacking Bob's system and changing Bob's operators. In this case, if, instead of attacking the entanglement source or Alice's system, Eve is able to get the malware into Bob's system, changing Bob's system's automated gate definition, so that an S gate is applied to Bob's qubit at the beginning of Bob's system's superdense coding operations, then, as shown in table 9, when compared with table 4's results, we also find that the hacked protocol leads to final state vectors that coincide with those that hold when Alice's system is hacked with the S gate added at the beginning of Alice's chain, attacking Alice's qubit.

Intended String	Final state vector with S
	gate at the beginning of
	Bob's chain
00	$ 0 angle \otimes rac{(1+i) 0 angle + (1-i) 1 angle}{2}$
01	$ 0 angle \otimes rac{(1-i) 0 angle + (1+i) 1 angle}{2}$
10	$ 1\rangle \otimes \frac{(1+i) 0\rangle - (1-i) 1\rangle}{2}$
11	$ 1\rangle \otimes \frac{-(1-i) 0\rangle + (1+i) 1\rangle}{2}$

Table 9: Final vectors resulting from the S gate malware at the beginning of Bob's chain.

By hacking Bob's qubit, this time at Bob's system, we get the same profile that we would get from attacking Alice's qubit directly at the beginning of Alice's chain as well as the same profile from hacking Bob's qubit at the end of the entanglement chain. As in the bijection attacks, we get a symmetry profile for hacking, by which different hacks lead to the same final result, this is strategically advantageous to the hacker, making it harder for quantum cybersecurity to find out which network node and qubit were attacked. In table 10 we show the results from simulating this last hacked protocol on ibmqx2.

Observed String	Intended String			
Observed String	00	01	10	11
00	46.1%	49.3%	7.9%	6.0%
01	45.8%	44.1%	8.1%	8.1%
10	5.6%	3.0%	43.4%	42.1%
11	2.5%	3.6%	40.6%	43.8%

Table 10: Simulation of the hacked protocol on ibmqx2, with the S gate operating on Bob's qubit at the beginning of Bob's operator chain. In each case, 1000 runs were used.

Looking at the final frequencies of measured strings and comparing with those of tables 5 and 7 we find that we cannot easily distinguish between the different attacks, indeed, from a quantum cybersecurity forensics standpoint, from the evidence of disruption on Alice's qubit, and having ruled out hardware malfunction or rise in environmental noise, the evidence is favorable to a hack. In the case of a software hacking targeting automated gate definition in the communications protocol, the only thing that can be inferred is the hypothesis that at least one of the communications network nodes and qubit have been attacked, but which node and qubit one cannot ascertain without inspecting each one for software changes, this is the main strategic advantage of quantum hacking symmetries that can be exploited by a quantum hacker.

As another example, for instance, Eve can obtain a similar final frequency profile upon measurement hacking Bob's system and Alice's qubit with a Hadamard gate applied to Alice's qubit at the end of Bob's circuit, in table 11 we show the simulation on ibmqx2 that results from applying this alternative hack, in this case, we have a similar measurement pattern but Eve used a different gate (a Hadamard gate rather than an S gate) and operated on Alice's qubit at the end of Bob's operator chain.

Observed String	Intended String			
Observed String	00	01	10	11
00	47.9%	41.7%	5.9%	9.3%
01	47.4%	50.9%	7.9%	8.2%
10	3.1%	4.9%	42.4%	42.2%
11	1.6%	2.5%	43.8%	40.3%

Table 11: Simulation of the hacked protocol on ibmqx2, with the H gate operating on Alice's qubit at the end of Bob's operator chain. In each case, 1000 runs were used.

These results show that different operators, attack nodes and qubits can all lead to similar quantum measurement frequency profiles, making it difficult to infer which node and qubit were actually attacked and what type of modification was actually used. The fact that attacking one qubit can lead to a disruption in another qubit, makes scrambling attacks on larger networks an effective security threat for quantum communications.

The implication of these results for cybersecurity is significant, since it provides an example of how one can hide a hack by attacking one qubit but in the end the disrupted qubit will be another one, that was never directly operated upon through the installed the malware, this is a specific feature of cyberattacks on quantum networks and communications' automated protocols: by strategically taking advantage of entanglement and symmetries for hacking quantum networked computation and communications makes it difficult to determine which systems and qubits were actually attacked.

In this sense, while a DDoS attack may be easier to detect as such, a quantum unitary scrambling attack, by compromising automation software with malware, may take a longer time to be uncovered, not only due to the need to rule out hardware malfunction or external factors like environmental noise that may have corrupted the quantum communications network, but also due to the the ability to propagate hacks from one attacked qubit to another, leaving the first attacked qubit unchanged at the final measurement, as exemplified above.

In the above example, since Alice's qubit was the one showing the increase in error with respect to the superdense coding protocol's unhacked output, while Bob's qubit followed the protocol with low noise deviations, one might waste time by first trying to find out if there was a hardware malfunction on each network node where computations were performed on Alice's qubit, and then, ruling out a physical source for the disruption, one might first try to find out if Alice's gate definition software for the protocol was hacked with installed malware. However, if no such malware is found on Alice's system, then, one would still have to check the entanglement source and Bob's system for possible malware, since Eve might have instead hacked Bob's system or the entanglement source, attacking either Alice's qubit or Bob's qubit, leading to the same disruption pattern on Alice's qubit, while leaving Bob's qubit with the correct main superdense coding pattern. From the observed frequencies, one cannot know exactly which node or qubit of the entangled pair was in fact attacked.

On a small network, such as the above, the forensic process may not take too long, however, when dealing with larger networks, it may indeed take a while to identify which systems and qubits were actually attacked, from the moment in which the attack is identified as such, since, by taking advantage of entanglement and symmetries, a hacker can mask the attacked nodes and qubits in such a way that upon measurement, the final disrupted qubit may not have ever entered an attacked system, the hack is effectively propagated from one qubit to another, due to the manipulation of entanglement and symmetries, while leaving the initial attacked qubit unchanged, as exemplified above for the superdense coding.

At this point, quantum cyberforensics becomes even more complex, since not only can different unitary gates lead to a similar measured profile but also the attacked systems can be masked through hack propagation, so that it becomes difficult to ascertain, especially in circuits that use quantum entanglement and symmetries, which endpoint was hacked. This gives a strategic and tactical advantage for short term quantum communications disruptions, coming from unitary scrambling attacks using unitary gates to induce deviations from automated communications protocols' intended outputs, producing random results upon measurement rather than the protocol's intended outputs, taking advantage of quantum randomness upon measurement.

Since the amplitudes are unobservable, only the final frequency distribution is available and since one cannot find out which systems or qubits were attacked just from observing the final measurement frequency distribution, as shown above, with different possible quantum malware attacks leading to the same final result, including even, also, the same final quantum amplitudes, a quantum measurement frequency analysis does not provide for a forensic basis on which to decide which networked systems and qubits were hacked. Only by looking for malware at each communication node can one find out where the malware was inserted.

In large quantum communications networks, with communications protocol

automation and multiple possible nodes attacked by malware installed to change automatic gate definition, unitary scrambling attacks can effectively lead to a propagation of hacks and disrupt a quantum communications network as well as distributed networked quantum computation, due to the exploitation of entanglement patterns and symmetries involved in quantum communications protocols for the process of quantum information transmission and processing, raising the error rates with respect to intended outputs and making it very difficult to find, from the final distribution, which nodes were attacked.

Eve can also attack multiple nodes, and produce disruptions on multiple qubits upon final measurement. As an example of malware attacking the automated protocol on two systems (the entanglement source and Alice), table 12 shows the results from a simulation of a two-point hack, when the intended string for the non-hacked circuit is 00, with an S gate attack at the end of Alice's computational chain and a \sqrt{X} gate attack applied to Bob's qubit at the end of the entanglement source's computational chain, as can be seen, the final frequencies seem to be close to an equiprobable distribution over the different four alternative strings. Indeed, the pattern observed in the simulations both for the qasm_simulator and the actual physical device (ibmqx2), shown in table 12, match well the theoretical probabilities, which, in this case are 0.25 for each string.

Intended String	Hacked Circuit	Hacked Circuit
	(qasm_simulator)	(ibmqx2)
00	24.5%	22.8%
01	23.7%	25.3%
10	25.1%	24.4%
11	26.7%	27.5%

Table 12: Simulation of the hacked circuit, on ibmqx2 and ibm_qasm_simulator, when the superdense coding protocol is applied for 00 message, with a \sqrt{X} gate applied on Bob's qubit at the end of the entanglement source's operations and the *S* gate malware at the end of Alice's chain. In each case 1000 runs were used.

In figure 4 we show the circuits for this attack, that we call $\sqrt{X} + S$ gate attack, for each alternative superdense coding circuit that makes up the superdense coding protocol.



Figure 4: Hacked superdense coding circuits with \sqrt{X} gate attack at the end of the entanglement source operations on Bob's qubit and S gate attack at the end of Alice's computational chain.

In each of the above circuits, upon measurement, we get an approximately 25% probability distribution over the four alternative strings, which comes from the fact that the final state vectors lead to an equiprobable distribution over the alternative values, a result that is due to the final state vector superposition configuration for each alternative activation of the superdense coding protocol, as we show in table 13.

Intended String	$\sqrt{X} + S$ gate attack state vectors
00	$rac{i 00 angle+ 01 angle+ 10 angle-i 11 angle}{2}$
01	$rac{ 00 angle+i 01 angle-i 10 angle+ 11 angle}{2}$
10	$rac{ 00 angle - i 01 angle + i 10 angle + 11 angle}{2}$
11	$\frac{-i 00\rangle+ 01\rangle+ 10\rangle+i 11\rangle}{2}$

Table 13: Final vectors resulting for each circuit in figure 4.

This last result shows how a hacker can disrupt several qubits simultaneously, in this case, Eve scrambles both Alice and Bob's qubits.

3 Conclusions and Discussion

We showed that superdense coding, with the automated communications protocol managed by software, is vulnerable to cyberattacks that come from malware targeting the automation software and changing the automated unitary gate definition, effectively changing the communications protocol. When communications are operating automatically, with the users not looking at the actual quantum gate sequence, this can lead to disrupted quantum communications and, also, disrupted quantum networked computation. We analyzed two types of attacks that can result from malware changing automated gate sequence definition in communications protocols, using superdense coding as an example. Both attack types involve unitary gate insertion at one or more communication nodes, changing the quantum computations performed at those nodes, however, the two attack types differ in the final profile and strategic intention.

The first attack type, which we called a bijection attack, works as a bijective remapping of the final transmitted message for each alternative message binary coding that Alice can send. This attack allows for Eve to change the message that Bob receives in a controlled way.

The second attack type, that we called unitary scrambling attack, operates so that the communications are scrambled, which means that upon measurement one or more qubits exhibit random fluctuations. This attack is more versatile in the sense that it can be employed for different operational profiles, namely, it can be used to produce final random results, upon measurement, for one, several or even all qubits.

To produce final random results upon measurement can be difficult to distinguish from hardware malfunction or sudden environmental noise increase, demanding an extra effort on the part of quantum cybersecurity forensics to identify the source of the disruption. Another advantage of producing random results at one or more attack target qubits is such that the hacker can exploit entanglement and symmetry, from a hacker's standpoint, this is one of its main effectivenesses since one can disrupt a target qubit by operating on another qubit of an entangled pair, thus propagating the hack from one qubit to another, making it difficult to ascertain which communications' node and qubit were attacked.

From a quantum cybersecurity standpoint, the results of the present work indicate the need to:

- 1. Develop research into quantum cyberforensic methods for investigating possible quantum cyberattacks on quantum communications and computation networks;
- 2. Develop research into protecting automation softwares for quantum gate definition in automated quantum communications protocols;
- Develop solutions for protecting quantum networks against such types of attacks;
- 4. Address the ways for remote deployment of the type of malware addressed in the present work, as well as the possibility of insider threat, which may be the greatest threat in the foreseeable future.

On the detection side, the possibility of sending a prearranged test message as a prefix key could be used to check for hacking of quantum communications, making it possible a faster identification of attacked nodes if measurements are periodically taken on specific nodes to check for anomalies. On the other hand, since, in the examples reviewed, we are dealing with a specific type of cyberattack in the form of malware that introduces software-level changes to quantum machine code automation and hardware implementation automation, with the objective of disrupting the communications protocol, by introducing a modified sequence of unitary operations depending on the messages that are being sent, so that the communications protocol is disrupted, in this way disrupting quantum communications and possible networked quantum computations, a counter for such an attack may involve the need to develop antivirus solutions aimed at checking this automation software for changes in the automatically coded circuits to be implemented by the quantum hardware, under the automated communications protocol.

As long as the antivirus is not itself hacked, this may provide for an immediate way to identify a change in automated gate sequence software and protect against the types of attacks addressed in the present work.

In the near future, remote cloud-based access to quantum computers can already be disrupted by such attacks as the ones addressed in the present work, aimed at rising the error level of quantum computations ran on these remote accessed systems, in this case, the threat is of change in coded translation from high level programming languages such as Python's Qiskit, for instance, into quantum machine language instructions remotely sent to the hardware, if this link is changed so that, for instance, a gate's specification is randomly changed at specific intervals (for instance, an X gate to a unit gate), then one could raise the error rate of these remotely accessed quantum computations, here the insider threat, aimed at hindering a company or other organization running the quantum hardware access is the greatest and near-future more feasible threat.

While the technical side of quantum cybersecurity may be concerned with the patterns and different types of attacks that can disrupt quantum communications and quantum networked computation, such a focus is incomplete if one does not consider the way in which these attacks can be operationally implemented by human beings, which leads us to a direct intersection with Intelligence Studies.

In our case, since the attack target is software, the hacker needs to conduct intelligence activities around the software systems used for quantum gate automation, and to find ways in which to deploy the malware, this intelligence gathering process and malware deployment will depend upon the organization, but, given the foreseeable nature of short to mid-term quantum communications, HUMINT activities will most probably be involved, heightening the insider threat.

Indeed, besides the threat from disgrunted employees that may deploy the malware, hacker teams, whether state-sponsored or not, may compromise people working for a target organization to gather intelligence and deploy malware. Another possibility is to infiltrate an organization using a covert operative to gather the intelligence on the gate specification and automation software and to find ways in which to break that organization's security protocols in order to deploy such a malware.

As quantum communications and quantum networked computation become

increasingly feasible, with the possibility of developping hybrid classical/quantum networks and even fully quantum intranets that may come to play a critical role in corporate, academia, defense, security and intelligence organizations. These systems will become strategically valued targets, especially for competitor states that are involved in a race for quantum supremacy, in this regard, threat coming from HUMINT activities targeting critical systems involved in quantum communications and in networked quantum computation will become a matter of concern from a National Security standpoint, especially taking into account the types of organizations that may be involved in the use of advanced quantum technologies. Future systematic studies are needed linking quantum cyberattacks and quantum malware patterns with Intelligence Studies in finding ways to deploy these attacks and how to counter them.

References

- **Abellan,** C. and Pruneri, V. (2018). "The future of cybersecurity is quantum". IEEE Spectrum, 55(7), 30-35. DOI: 10.1109/MSPEC.2018.8389185.
- Bennett C.H. and Wiesner S.J. (1992). "Communication via one- and twoparticle operators on Einstein-Podolsky-Rosen states". Phys. Rev. Lett. 69, 2881. DOI: 10.1103/PhysRevLett.69.2881.
- Cross, A.W., Bishop L.S., Smolin J.A., Gambetta J.M. (2017). Open Quantum Assembly Language. arXiv:1707.03429 [quant-ph]. Retrieved from: https://arxiv.org/pdf/1707.03429.pdf.
- **Cross** A. (2018). "The IBM Q experience and QISKit open-source quantum computing software". Bull. Am. Phys. Soc. 63.
- Gerhardt I., Liu Q., Lamas-Linares A., Skaar J., Kurtsiefer C., Makarov V. (2011). "Full-field implementation of a perfect eavesdropper on a quantum cryptography system". Nature Communications, 2:349. DOI: 10.1038/ncomms1348.
- Gonçalves, C.P. (2017). "Quantum Neural Machine Learning: Backpropagation and Dynamics". NeuroQuantology, 15, (1), 22-41.
- Gonçalves, C.P. (2019). "Quantum Neural Machine Learning Theory and Experiments". In Aceves-Fernandez, M.A. (ed.), Machine Learning in Medicine and Biology, IntechOpen, DOI: 10.5772/intechopen.84149.
- Gompert, D.C. and Libicki M. (2021). "Towards a Quantum Internet: Postpandemic Cyber Security in a Post-digital World". Survival – Global Politics and Strategy, 63(1), 113-124. DOI: 10.1080/00396338.2021.1881257.
- Hugues-Salas E., Ntavou F., Ou Y., Kennard J. E., White C., Gkounis D., Nikolovgenis K., Kanellos G., Erven C., Lord A., Nejabati R., Simeonidou D. (2018). "Experimental Demonstration of DDoS Mitigation over

a Quantum Key Distribution (QKD) Network Using Software Defined Networking (SDN)". Optical Fiber Communication Conference, OSA Technical Digest (Optical Society of America), paper M2A.6, retrieved from: https://www.osapublishing.org/viewmedia.cfm?uri=OFC-2018-M2A.6&seq=0.

- Jogenfors J., Elhassan A.M., Ahrens J., Bourennane M., Larss J.-Å. (2015). "Hacking the Bell test using classical light in energy-time entanglement based quantum key distribution". Science Advances (1) 11: e1500793. DOI: 10.1126/sciadv.1500793.
- Larsson J.-Å. (2002). "A practical Trojan Horse for Bell-inequality-based quantum cryptography". Quantum Inf. Comput. 2, 434-442.
- Lydersen L., Wiechers C., Wittmann C., Elser D., Skaar J., Makarov V. (2010). "Hacking commercial quantum cryptography systems by tailored bright illumination". Nat. Photon. 4, 686-689.
- Makarov V. and Hjelme D. (2005). "Faked states attack on quantum cryptosystems". Journal of Modern Optics, 52(5), 691-705.
- Mailloux, L. O., Hodson, D. D., Grimaila, M. R., McLaughlin, C. V, Baumgartner, G. B. (2016a). "Quantum Key Distribution: Boon or Bust". Journal of Cyber Security & Information Systems, 4(2), 18-25.
- Mailloux, L.O., Lewis II C.D., Riggs C., Grimaila M.R. (2016b). "Post-Quantum Cryptography: What Advancements in Quantum Computing Mean for IT Professionals". IT Professional, 18(5), 42-47.
- Satoh T., Nagayama S., Suzuki S., Matsuo T., Van Meter R. (2020). "Attacking the Quantum Internet". arXiv:2005.04617 [quant-ph], retrieved from: https://arxiv.org/pdf/2005.04617.pdf.
- Satoh T., Nagayama S., Oka T. and Van Meter R. (2018). "The network impact of highjacking a quantum repeater". Quantum Science and Technology 3(3): 034008.
- Schartner P. and Rass S. (2010). "Quantum key distribution and Denial-of-Service: Using strengthened classical cryptography as a fallback option". International Computer Symposium (ICS), Taiwan.
- Wu L.-A. and Lidar D. (2006). "Quantum Malware". Quantum Information Processing 5: 69–81. DOI: 10.1007/s11128-006-0014-5.
- **Zygelman** B. (2018). "A First Introduction to Quantum Computing and Information". Switzerland, Springer.