Shuttle-Exploiting Attacks and Their Defenses in Trapped-Ion Quantum Computers

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Abstract—Trapped-ion (TI) quantum bits are a front-runner technology for quantum computing. TI systems with multiple interconnected traps can overcome the hardware connectivity issue inherent in superconducting qubits and can solve practical problems at scale. With a sufficient number of qubits on the horizon, the multi-programming model for Quantum Computers (QC) has been proposed where multiple users share the same QC for their computing. Multi-programming is enticing for quantum cloud providers as it can maximize device utilization, throughput, and profit for clouds. Users can also benefit from the short wait queue. However, shared access to quantum computers can create new security issues. This paper presents one such vulnerability in shared TI systems that require shuttle operations for communication among traps. Repeated shuttle operations increase quantum bit energy and degrade the reliability of computations (fidelity). We show adversarial program design approaches requiring numerous shuttles. We propose a random and systematic methodology for adversary program generation. Our analysis shows shuttle-exploiting attacks can substantially degrade the fidelities of victim programs by \( \approx 2X \) to \( \approx 63X \). Finally, we present several countermeasures such as adopting a hybrid initial mapping policy, padding victim programs with dummy qubits, and capping maximum shuttles.

Index Terms—Trapped-ion, qubit, quantum computing, shuttle, security, fidelity.

I. INTRODUCTION

Quantum computing has garnered immense attention from industry and academia alike in recent years as a quantum computer can potentially speed up certain classes of problems beyond the means of classical computers. It can be advantageous in domains like machine learning [1], drug discovery [2], molecule simulation [3], [4], and optimization [5]. With an active interest in the field, quantum computing is progressing at a rapid pace. On one hand, researchers are exploring new quantum algorithms that leverage unique properties like superposition, entanglement, and interference to speed up computation. On the other hand, researchers are pursuing various technologies like superconducting, trapped-ion (TI), and photonics to design quantum bits or qubits. The quantum hardware is also improving over time (i.e., size and quality).

The TI qubit is one of the most promising technologies for building a quantum computer. It offers several advantages such as identical qubits, long coherence times, and all-to-all connectivity among qubits [6]. Several companies such as IonQ and Honeywell are developing TI systems. Recently, Honeywell reported a trapped-ion system with quantum volume (QV) of 512 [7], highest thus far (QV is a metric proposed by IBM [8] to quantify the capabilities of a quantum computer). Some of these TI qubit-based systems are also commercially available via IBM Qiskit [9], [10], Amazon Braket [11], and Microsoft Azure Quantum [12]. Although existing TI systems have a smaller number of qubits compared to their superconducting counterparts (IBM Quantum Eagle processor has 127 qubits whereas largest known trapped-ion system has 11 qubits [6]), road-maps for larger systems with 50-100 qubits are in place [13], [14]. Confining many ions in a single trap becomes problematic from a control and gate implementation perspective. Therefore, the pathway to scalability in TI systems involves multiple interconnected traps. A technology named quantum charge-coupled device (QCCD) is proposed in [15] for scalable and modular trapped-ion systems. In this light, Murali et al. [16] performed extensive architectural studies for multi-trap trapped ion systems. They developed a compiler and a simulator [17] for such systems with experimentally calibrated values. With industrial and academic efforts, the future of the TI system looks promising.

Fig. 1 shows a TI quantum computer diagrammatically. In a TI system, qubits are realized using ions. Data is encoded as ion’s internal states. Ions are confined inside traps using direct current and oscillatory potentials (thus, we use the terms ions and qubits interchangeably for TI systems in this...
In this paper, we present an attack in the multi-programming setting for TI systems by exploiting a new vulnerability in terms of shuttle operations. Fig. 1 provides an overview of the proposed attack model. We assume qubits from the adversary program span over two traps, and they share a trap with qubits with the victim program. For example, adversary and victim qubits share Trap–1 (T1). The adversary can design his/her program such that it requires computation (gate) between ions from different traps that will need frequent shuttles between traps. Repeated shuttling adds energy to an ion and increases an ion-chain’s energy. This elevated chain-energy degrades the reliability of computation (known as gate fidelity). As victim qubits share a chain (ion-chain in T1) with the adversary qubits, they also suffer from this shuttle-induced fidelity degradation. Although the premise seems simple, there are architectural policies that curbs shuttling and make the attack challenging. Thus, the attack culminates into designing a program that will trick the architectural policies and enforce repeated shuttles. The attack can be launched in a white-box setup where the attacker knows the policies and beats them to achieve repeated shuttles (Section V). Or, it can be a black-box type attack where no prior information is known (Section IV).

With the rapid advancement of quantum hardware, quantum algorithm, and quantum architectures, quantum cloud services will become more practical and popular. Now is an opportune time to identify vulnerabilities in and devise appropriate defenses for imminent multi-programming quantum clouds to prepare for practical scale cloud deployments. This paper is one of the first efforts towards this goal.

We make the following contributions in this paper:

- Identify repeated shuttle operations as a mode of attack.
- Present two malicious program generation methodologies - systematic and random. Systematic attack uses prior knowledge about architectural policies to design a strong attack. The random attack does not require any prior knowledge, albeit losing some attack potency.
- Modify the QCCD-Compiler [16], [17] to accommodate multi-programming. We use QCCD-simulator and QCCD-compiler interchangeably in this paper since the compiler and the simulator are a part of the same software tool-chain.
- Analyze the impact of trap capacity and victim size on shuttle number and fidelity reduction of the victim.
- Discuss three countermeasures to thwart attacks.

The outline of the paper is as follows: Section II discusses the basics of quantum computing and TI systems. Section III describes the attack model and the simulation setup for analyses in this paper. Section IV delineates the methodology of systematic malicious program generation. Section IV discusses the random attack program designing principles. Section VI reports the results and discussions. Section VII presents several countermeasures. Finally, Section VIII draws conclusion.

1We use the following definitions for program size and program length: program size is the number of qubits in a program and program length is the number of 2-qubit gates in the program.
II. BASICS

In this section, we discuss the basics of trapped-ion quantum computers and terminologies used in the paper.

A. Qubit and quantum gate

1) Qubits: Quantum bits or qubits are the building block of a quantum computer. Qubits store data (i.e., \( |0 \rangle \) and \( |1 \rangle \)) as various internal states. A qubit can be in both \( |0 \rangle \) and \( |1 \rangle \) simultaneously due to quantum superposition property. A qubit state is represented as \( |\psi\rangle = a|0\rangle + b|1\rangle \) where \( a \) and \( b \) are probabilities amplitudes. Measuring the qubit will collapse one state and return classical bits 0 or 1 with probabilities \( |a|^2 \) and \( |b|^2 \), respectively.

2) Quantum gates: Quantum gates manipulate information stored in qubits to perform computation. Quantum gates are realized using pulses such as radio frequency (RF) and laser pulses. Gate pulses modify the probability amplitudes of a qubit. For example, a quantum NOT (X) gate pulse when applied to a qubit at state \( |0\rangle \) will change amplitudes \( a = 1 \) and \( b = 0 \) to \( a = 0 \) and \( b = 1 \). Quantum gates are reversible in nature and represented by unitary matrices mathematically.

At present, the physically realized gates are 1-qubit and 2-qubit. A quantum program is a sequence of quantum gates.

Fig. 3 shows a sample quantum program consisting of 2-qubit Mølmer–Sørensen (MS) gates [25].

3) Gate fidelity: Quantum gates in existing quantum computers are erroneous. They incur a finite and non-negligible error rate (\( \epsilon \)) when executed. Suppose the aforementioned X gate is applied on state \( |0\rangle \) for 10,000 times. One would, in theory, get output 1 all the time. However, due to gate errors, the user may end up with 9,900 1’s (correct) and 100 0’s (incorrect). The gate fidelity (\( F \)) is usually defined as the complement of the error rate i.e., \( F = 1 - \epsilon \). It depends on variations of control pulses and environmental interference. Qubits are kept and operated in a controlled environment to shield them from various noises so that gate fidelities can be high. A lower gate fidelity will introduce more errors in the output and can completely decimate the result.

B. Trapped-ion QC

1) Trap details: In a trapped-ion system, atoms like Yb or Ca are ionized and trapped between electrodes using electromagnetic fields. Hence, the name trapped-ion quantum computer. Data \( |0\rangle \) and \( |1\rangle \) are encoded as internal states such as hyper-fine or Zeeman states of the ions. Fig. 1 shows the schematic of a trapped-ion system. It has 2 traps: Trap 0 or T0 and Trap 1 or T1. Inside the traps, ions form chains. The traps are connected by a shuttle path which allows movement (shuttle) of an ion from one trap to another if needed. Traps can accommodate a certain number of ions known as trap capacity. For example, traps in Fig. 1 have a trap capacity of 4 ions per trap. Besides, some capacity is reserved for incoming ions from other traps known as communication capacity. The communication capacity is not shown explicitly in Fig. 1 however, an ion can be moved from T0 to T1, and in that case, T1 will hold 5 ions. Thus, the trap capacity + communication capacity defines the absolute maximum number of ions a trap can hold. Communication capacity is much smaller than trap capacity in general [16]. Finally, the excess cap (EC) of a trap is defined as trap capacity + communication capacity - ions in the trap.

2) Gate details: Laser pulses are used to perform quantum gate operations on the qubits/ions. Mølmer–Sørensen (MS) gate is the typical native 2-qubit gate of trapped-ion systems [28]. It is accompanied by several 1-qubit gates which are mainly rotation gates to form a universal gate-set. For example, the 1-qubit gates are GPI, GPI2, and GZ in the IonQ computer. Data \( |0\rangle \) and \( |1\rangle \) are encoded as internal states such as hyper-fine or Zeeman states of the ions. Fig. 1 shows the schematic of a trapped-ion system. It has 2 traps: Trap 0 or T0 and Trap 1 or T1. Inside the traps, ions form chains. The traps are connected by a shuttle path which allows movement (shuttle) of an ion from one trap to another if needed. Traps can accommodate a certain number of ions known as trap capacity. For example, traps in Fig. 1 have a trap capacity of 4 ions per trap. Besides, some capacity is reserved for incoming ions from other traps known as communication capacity. The communication capacity is not shown explicitly in Fig. 1 however, an ion can be moved from T0 to T1, and in that case, T1 will hold 5 ions. Thus, the trap capacity + communication capacity defines the absolute maximum number of ions a trap can hold. Communication capacity is much smaller than trap capacity in general [16]. Finally, the excess cap (EC) of a trap is defined as trap capacity + communication capacity - ions in the trap.
The program execution will start with this allocation, and the weights \( wt \). A quantum program can be treated as a graph \( T_0 \). The gate fidelity equation \( 16 \) for TI systems. This is an experimentally validated gate fidelity model. Here, \( \Gamma \) is the trap heating rate, \( \tau \) is the gate time, and \( \tilde{n} \) is the vibrational energy or motional mode of a chain. \( A \) is a scaling factor that depends on the number of ions in the chain as \( N/\ln(N) \). The gate fidelity will degrade if gate time and/or motional mode of the chain increases. A 2-qubit gate cannot be applied to ions from different traps. It requires a shuttle.

3) Need of shuttle operation: Consider the sample program in Fig. 3a. The 4th gate in the program MS \( q[a0], q[a1] \) involves ions from the same trap (Trap 0) and can be executed in-place or directly (Fig. 3b). However, the 8th gate MS \( q[a1], q[a5] \) involves ions from different traps (Fig. 3). Therefore, a shuttle is needed to bring the ions in the same trap.

4) Shuttle steps: The shuttle operation involves several steps as depicted in Fig. 4. First, \( a1 \) and \( a2 \) are swapped so that \( a1 \) is transferred near the shuttle path. Then, \( a1 \) is split from the chain-0 and shuttled/moved from T0 to T1. The shuttle operation adds energy to the ion. Then, \( a1 \) is merged to the chain-1. This merge operation increases the vibrational energy \( (\tilde{n}) \) of chain-1. Finally, MS \( q[a1], q[a5] \) can be executed as the ions are in the same trap (T1) now. As chain-1’s \( \tilde{n} \) is now higher, the subsequent gate operations in this chain (either on aX ions or vX ions) will experience lower fidelity \( (F) \). Increasing a chain’s motional mode by repeated shuttles is the basis of the attack proposed in this paper.

C. Initial mapping policy

The initial mapping - in this context - entails the assignment of program qubits in traps (i.e., mapping of logical qubits to physical traps) and the relative position of qubits inside a trap. For example, the program qubits \( (a0 \) to \( a5 \)) from the sample program in Fig. 3a are initially mapped as T0: \[ a0, a3, a1, a2 \], T1: \[ a4, a5 \] (explained in Example 2.1). The program execution will start with this allocation, and the mapping will be updated based on shuttles.

The initial mapping policy in \( 16 \) is the greedy policy where qubits are allocated in the descending order of edge weights \( wt \). A quantum program can be treated as a graph where each node represents a qubit and an edge between two qubits represents a 2-qubit gate. Thus, the edge weight represents the frequency of a 2-qubit gate between a pair of qubits. In the Greedy policy, the qubits of the most frequent gates are allocated first.

Example 2.1: The mapping policy and the result can be explained with the sample program in Fig. 3. The edge weights of the program are as follows: \( wt(a0, a3) = 3 \) (as the MS \( q[a0], q[a3] \) gate appears 3 times throughout the program), \( wt(a1, a2) = 2 \), and \( wt(a0, a1) = wt(a4, a5) = wt(a1, a5) = 1 \). Therefore, ions \( a0 \) and \( a3 \) are allocated first, then \( a1 \) and \( a2 \), and finally, \( a4 \) and \( a5 \). In this example, we assume a trap capacity of 4. Thus, ions \( a4 \) and \( a5 \) are in T1.

D. Shuttle direction policy

Shuttle direction policy dictates which ion will be moved to execute a 2-qubit gate. The shuttle direction policy used in the QCCD compiler \( 16 \) is illustrated in Listing 1. In this paper, we follow the same shuttle direction policy. In the example from Fig. 3 both traps have an equal number of ions. Hence, they have the same excess capacity (= trap capacity – # ions in the trap). Thus, the first ion \( a1 \) in the MS \( q[a1], q[a5] \) is shuttled from T0 to T1.

Listing 1: Shuttle direction policy \( 16, 17 \).

E. Multi-programming

The proposed attack model exploits the multi-programming setup. We modify the initial mapping policy \( 16, 17 \) to allow for multi-programming as follows: Suppose, we have two traps (T0 and T1) and two programs (prog-0 and prog-1). We allocate prog-0 from one end of the T0 to T1 (if needed) and prog-1 from the opposite end of the T1 to T0. Qubits in a single program are allocated per the greedy mapping policy \( 16 \). Allocating multiple programs from opposite ends and different traps ensures that qubits of one program are not mixed with the other program.

III. ATTACK MODEL AND SIMULATION SETUP

A. Attack model

The following assumptions are made in the attack model:

- More than one program are running on the QC.
- The adversary program spans more than one trap, and it shares one trap with another (victim) program.
- The adversary knows device specification such as trap capacities and communication capacities. This information (especially, trap capacities) are usually public information. For example, the Honeywell H0 TI system has a capacity of 6 \( 31 \).
- Adversary knows architectural policies: initial mapping policy and shuttle direction policy (can be relaxed). Rational behind the assumption is discussed in Section V-E3.
- The adversary can access the compiled program. This is a reasonable assumption because present quantum clouds provide such access. It allows a user to identify bottlenecks and optimize their programs. For example, in AWS Braket the compiled program is available to the user as the MetaData \( 32 \).
The adversary designs his/her program so that it requires repeated shuttles increasing the vibrational energy of the shared ion-chain and degrading gate fidelities. Note that, the adversary program fidelity takes a hit as a byproduct. However, the objective of the attack is to affect the victim program.

We present two techniques of devising the attack programs: systematic (Section IV) and random (Section V). On one hand, systematic program generation requires several prior information such as initial mapping and shuttle direction policies. However, it guarantees a linear increase in the number of shuttles (desired) with increased program length. On the other hand, random generation does not guarantee a linear increase of shuttles but requires no prior knowledge. Nevertheless, both methods can degrade victim performance (Section VI).

B. Simulation setup

In this paper, we use the QCCD compiler-simulator [17] accompanying the paper [16] to perform simulations. The QCCD compiler takes care of the initial mapping, shuttle insertion, gate scheduling, and fidelity computation of a program. We add our modification on top of the QCCD compiler to allow for multi-programming. Our tweaks include: (i) modifying initial mapping to map multiple programs (as in Section ILE) to the device and (ii) reporting individual program fidelities.

For all simulations, we assume a device with 2 traps connected in a linear fashion as in Fig. [1]. The trap capacity is 15 ions per trap with 2 additional spaces per trap for incoming (shuttled) ions (communication capacity). We also show analysis for trap capacities 20 and 25 (with the same communication capacity of 2). The trap capacity values of 15 to 25 are selected as per [16] as they observed better performance in this range.

We set the adversary program size to 18 qubits (trap capacity 15 + 3) so that it spans two traps. We vary victim program sizes from 2 to maximum remaining space in shared trap T1 i.e., 12 qubits. Note that the adversary and the victim program sizes will change accordingly for trap capacities 20 (23 and 2 to 17 respectively) and 25 (28 and 2 to 22 respectively).

2-qubit gates mostly affect the program fidelity as they have an order of magnitude lower fidelity than 1-qubit gates. Therefore, we consider only the 2-qubit gate fidelities without any loss of generality in our analysis. The QCCD-simulator [16], [17], includes experimentally calibrated parameters [27], [29], [33], [34] for the gate fidelity equation in Fig. 2. The program fidelity is computed from individual gate fidelities ($F$).

For a program with $k$ 2-qubit gates ($g_i$), $i$ being an enumeration parameter across the 2-qubit gates, the program fidelity is $F(g_0) \times F(g_1) \times \ldots \times F(g_{k-1})$.

IV. RANDOMIZED MALICIOUS PROGRAM

In this section, we discuss randomized malicious program generation. The randomized attack programs are advantageous as they treat the compiler as a black-box and do not need information about compiler policies. We present a methodology to find and refine an effective random program to launch attacks. The only requirement is that the adversary can submit many programs to the cloud and can access the final compiled program. The final shuttle-inserted compiled-program will tell the adversary which program resulted in maximum shuttles. The adversary will pick that program to launch future attacks.

A. General methodologies

We populate the program with ($18\choose2$) gates (all 2 qubit combinations from 18 qubits adversary size with trap cap 15). Then, we randomly shuffle the gate orders to generate the random program.

We generate 1000 random circuits and compile them with pseudo-victim programs of sizes from 2 to 12 qubits. The idea of a pseudo-victim program is that the adversary will send two programs to the cloud to mimic an adversary-victim pair. After analyzing the collected results, the adversary can select the random circuit that gives the highest average number of shuttles across victim programs of all sizes.

B. Pruning the random circuit

The best random circuit can be pruned further as not all the gates contribute to shuttling. The intuition is that we can remove some gates from the random circuit without lowering the number of shuttles. The pruning logic is as follows: we remove one gate from the original random circuit starting from the first gate, compile it, and check the number of shuttles. If the number of shuttles does not drop from the original case, we permanently remove the gate from the circuit and move on to the next gate. If removing the gate lowers the number of shuttles, we reinsert the gate and move on to checking the next gate. Following this step-by-step check, we can remove some redundant gates without affecting the number of moves. The pruning on average removed $\approx 48$ gates from the program of 153 gates.

V. SYSTEMATIC MALICIOUS PROGRAM

A. Basic idea

The systematic method of malicious program generation uses the following 3 ingredients to craft a strong attack program: (i) initial mapping policy, (ii) shuttle direction policy, and (iii) information on the victim size. As mentioned earlier, a gate will require a shuttle when the ions belong to two different traps. This principle is leveraged in the systematic method, and gates are added in the malicious program with ions from different traps. However, this approach requires knowledge about ion locations, and the above 3 ingredients facilitate the tracking of ion locations.

Our proposed systematic malicious program consists of three blocks: (i) shuttle controller (SC), (ii) a bridging gate, and (iii) initial mapping controller (IMC). Each block is generated using specific logic as explained later in this section. After all blocks are generated, they are stitched to create the complete malicious program (i.e., malicious program = shuttle controller + a bridging gate + initial mapping controller).

The IMC block is generated first, then the SC block, and finally the bridging gate, although they appear in a different order in the program. This ensures no gate from the SC block
Algorithm 1: Create initial mapping controller block.

| Input: trap capacity |
|----------------------|
| Output: initial mapping controller |
| ion_list = [0 to (trap capacity − 1)]; |
| ion_a, ion_b ← 2 arbitrary ions from ion_list; |
| add gate (ion_a & ion_b) twice in the initial mapping controller block; |
| remove ion_a & ion_b from ion_list; |
| while ion_list is not empty do |
| ion_a ← ion_b from last gate; |
| ion_b ← next ion from ion_list; |
| add gate (ion_a & ion_b) twice in the initial mapping controller block; |
| remove ion_b from ion_list; |
| end |

Fig. 5: IMC block of the malicious program. Arrows showing dependency between gates.

and the bridging gate have a higher edge weight than gates from the IMC block (explained more in Section V-E1).

B. Initial mapping controller

With knowledge about the initial mapping policy, the adversary can intelligently add gates in the program to force a known initial mapping. As described in Section II-C, the initial mapping policy in the QCCD Compiler is a greedy one that allocates ions based on gate frequencies (edge weights). Therefore, the adversary can judiciously increase edge weights between certain nodes (ions/qubits) which he/she wants to be allocated first. Algorithm 1 illustrates the gate selection methodology. We explain the algorithm with Example 5.1.

Example 5.1: Suppose, the trap capacity is 15. Thus, the ion_list will be [0, 1, 2, ..., 13, 14]. Next, we arbitrarily select two ions 0 (ion_a) and 1 (ion_b) from the list. Note that any two ions can be selected. We add gate MS q[0], q[1] twice in the program with these ions. This will make edge weight of (0, 1) = 2. Next, ions 0 and 1 are removed from the ion_list which now becomes [2, 3, 4, ..., 13, 14].

Next, ion_a and ion_b values are updated. ion_a’s value becomes the previous ion_b value (i.e., 1), and ion_b’s value becomes the next value from the ion_list (i.e., ion_b = 2). Then, the gate with these two ions - MS q[1], q[2] - are added twice in the block. Finally, ion_b = 2 is removed from the ion_list for this iteration, and ion_list becomes [3, 4, 5, ...

Fig. 6: (a) The partial SC block, showing first and last few gates. (b) The bridging gate between the shuttle controller and the initial mapping controller block. Only one bridging gate is necessary between these blocks.

..., 13, 14]. The above routine is repeated unless the ion_list becomes empty i.e., all the ions are added in the block.

The final IMC block will be similar to Fig. 5. All the gates in the block have an edge weight of 2. The logic in the other blocks (SC block and bridging gate) ensures that no other edge weight exceeds 1 (i.e., all other gates will appear once). Due to the higher edge weights, gates in the IMC block will be allocated first according to the greedy policy. Thus, ions 0 to 14 (15 qubits) will be allocated first to T0 (the remaining 3 qubits of the 18 qubit adversary will be allocated to T1 by default).

Assuming a victim size of 12, the trap states after initial mapping will be {T0 (EC = 2): [0, 1, 2, ..., 13, 14], T1 (EC = 2): [15, 16, 17] + [12Q victim]}. Here, EC = excess capacity. T0 has 15 ions from adversary program. T1 also has 15 ions, 3 from the adversary and 12 from the victim. Thus, each trap has an excess capacity of 2 (from communication capacity).

C. Shuttle controller

After the IMC block ensures a known initial mapping, we use Algorithm 2 to add gates in the malicious program that require shuttles. The flow consists of 5 steps. We explain each step in Example 5.2. The core idea is to track ion locations (using shuttle direction policy) after each gate and select ions from different traps for the next gate.

Example 5.2:

Step–1: For the very first gate, we randomly select 1 ion from adversary’s ion list (i.e., from [0 to 17] for the 18-qubit adversary). Suppose, the selected ion is 14 (i.e., ion_a = 14).

Step–2: From the initial mapping, we know ion 14’ is in T0. Therefore, the opposite trap is T1.

Step–3: Select ion 15 from T1. Check if gate MS q[14], q[15] does not exist in the program (i.e., edge weight of (14, 15) is 0 in the program graph). As the gate does not exist in the program, we do not check more ions from T1 and can break from the loop with ion_b = 15.
Algorithm 2: Create shuttle controller block

Input: trap states, shuttle direction policy, node weights, edge weights, block length, prog. size
Output: shuttle controller block (sc_block)

1. sc_block ← empty; # of added gates ← 0; flag ← 0;
2. while # of added gates < block length do
   // STEP – 1;
   if # of added gates == 0 then
      ion_a ← random ion ∈ {0 to prog. size – 1};
   else if flag == 0 then
      ion_a ← moved ion from last gate;
   else
      ion_a ← non-moved ion from last gate;
   end
3. // STEP – 2;
4. get ion_a’s location; get opposite_trap;
5. // STEP – 3;
6. for ion_b ∈ {ions in the opposite trap} do
7.    if edge weight (ion_a, ion_b) == 0 then
8.      flag ← 0; break;
9.    else
10.       flag ← 1; continue;
11.    end
12. end
13. if flag == 1 then
14.      continue;
15. end
16. // STEP – 4;
17. sc_block ← sc_block + gate (q[ion_a], q[ion_b]);
18. last_gate ← (ion_a, ion_b);
19. // STEP – 5;
20. identify moved ion, update node and edge weights,
21.    update trap states using shuttle policy;
22. # of added gates ← # of added gates + 1
23. end

Step-4: Add gate MS q[14], q[15] in the program. This gate will require a shuttle when executed. Therefore, trap states need updating after the gate.

Step-5: Both T0 and T1 have equal excess capacity of 2 each. Therefore, according to the shuttle direction policy in Listing 1, the first ion in the gate MS q[14], q[15] i.e., ion 14 will move from T0 to T1. Thus, the updated trap states are {T0 (EC = 3): [0, 1, 2, ..., 13], T1 (EC = 1): [14, 15, 16, 17] + [(12q victim)]}. (Note, the victim size information is required to compute the excess capacity of the shared trap T1 and to find the shuttle direction accurately.) Edge weights list is updated with the new gate.

Following the same routine, we keep adding gates in the malicious program until target number of gates are reached. For the next iteration, we pick ion 14 (moved ion from the last gate) as the ion_a in Step-1. As ion 14 is in T1 now, we pick the other ion from T0 (say, ion 2). The next gate is MS q[2], q[14]. As T0 has more EC (= 3) than T1 (EC = 1), ion 14 will again move but this time from T1 to T0. Finally, the updated trap states after this gate will be {T0 (EC = 2): [0, 1, 2, ..., 13, 14], T1 (EC = 2): [15, 16, 17] + [12q victim]}. A partial shuttle controller block of block length 80 is illustrated in Fig. 6b. Note the last gate in the block. It is required for the bridging gate.

D. The bridging gate and the complete malicious program

1) The bridging gate: The bridging gate is formed by taking one ion from the last gate of the shuttle controller block and one ion from the first gate of the initial mapping controller block (Fig. 6b). As the name suggests, this gate bridges two blocks and maintains the gate dependency. Only one bridging gate is necessary.

2) The complete malicious program: The complete malicious program is created by combining individual parts in the following order: gates from the SC block + bridging gate + gates from the IMC block.

E. Discussions on the systematic method

1) Out-of-order IMC block: In greedy policy, ions from a gate is primarily mapped based on their frequency of appearance and secondarily by their order of appearance in the program. Gates in the IMC block have the highest frequencies across the complete program because they each are deliberately added twice in the program, and gates from the other blocks each are added once. Generating the IMC block first ensures that other blocks can skip gates already in the IMC block. The compiler sorts gates in the descending order of their frequencies for mapping. Therefore, gates in the IMC block come first in the sorted list for mapping although they appear last in the malicious program.

2) Necessity of victim size information: The victim size is a parameter of the SC block generation algorithm. If the victim size is correct, each gate in the generated SC block will require one shuttle when the malicious program is executed. However, with an inaccurate victim size, some of the gates in the SC block will not force a shuttle.

Example 5.3: Consider the SC block in Fig. 6h generated assuming a victim size of 12. Suppose, the actual victim size during run is 5. Then, the actual trap
TABLE I: Statistics from victim size-assumption sweep for trap cap = 20 Trap cap = 25

| Victim size asmp. | Trap cap = 20 | Trap cap = 25 |
|-------------------|--------------|--------------|
| | AVG | STD | ICV | AVG | STD | ICV |
| 2 | 50.12 | 14.96 | 0.77 | 60.29 | 12.92 | 1.21 |
| 3 | 62.19 | 11.18 | 1.28 | 58.62 | 10.75 | 1.41 |
| 4 | 51.06 | 15.88 | 0.74 | 50.48 | 16.92 | 0.77 |
| 5 | 66.25 | 9.97 | 1.53 | 59.24 | 14.38 | 1.07 |
| 6 | 57.19 | 15.12 | 0.87 | 51.38 | 16.6 | 0.8 |
| 7 | 64.94 | 9.04 | 1.66 | 62.38 | 11.36 | 1.42 |
| 8 | 58 | 12.34 | 1.08 | 54.57 | 15 | 0.94 |
| 9 | 68.88 | 7.41 | 2.14 | 61.9 | 10.18 | 1.58 |
| 10 | 61.69 | 9.79 | 1.45 | 57.14 | 13.59 | 1.09 |
| 11 | 64.38 | 9.1 | 1.63 | 66.57 | 8.27 | 2.09 |
| 12 | 62 | 8.76 | 1.63 | 59.86 | 10.9 | 1.42 |
| 13 | 67.25 | 6.75 | 2.3 | 64.76 | 7.78 | 2.16 |
| 14 | 67.12 | 7.62 | 2 | 59.38 | 10.73 | 1.43 |
| 15 | 65.62 | 7.97 | 1.9 | 66.33 | 6.83 | 2.52 |
| 16 | 65.62 | 7.97 | 1.9 | 62.76 | 8.29 | 1.96 |
| 17 | - | - | - | 65.62 | 6.95 | 2.45 |
| 18 | - | - | - | 67.86 | 7.19 | 2.45 |
| 19 | - | - | - | 67.86 | 7.19 | 2.45 |
| 20 | - | - | - | 65.05 | 7.76 | 2.17 |
| 21 | - | - | - | 65.05 | 7.76 | 2.17 |
| 22 | - | - | - | 65.05 | 7.76 | 2.17 |

Fig. 8: Effect of victim size assumption (trap capacity = 15). Assuming victim size 8 provides best result across all actual victim sizes (highest ICV).

VI. RESULTS AND DISCUSSIONS

A. Victim size sweep

1) Systematic attack: Fig. 7 shows the number of shuttles for various actual victim sizes (2 to 12, trap cap 15) where the attack program is designed assuming a 2-qubit victim. The plot shows the highest number of moves (80) is achieved when adversary assumption matches actual victim size (dark bar in the plot). We also observe that for other actual victim sizes shuttle numbers vary and typically drop from the highest value. We report the mean (µ), standard deviation (σ), and inverse of coefficient of variation (ICV) of this distribution.

Table I: Statistics from victim size-assumption sweep for trap caps 20 and 25. For trap cap 20, assuming a victim size of 13 will provide best result (high ICV) across all actual victim sizes, and for trap cap 25 the best assumption is 16.
TABLE II: Shuttle statistics for the random attack.

| Victim size | Trap cap = 15 (random attack) | Victim size | Trap cap = 15 (random attack) |
|-------------|--------------------------------|-------------|--------------------------------|
|             | AVG | STD | ICV | AVG | STD | ICV | AVG | STD | ICV |
| 2           | 42  | 10.13 | 1.17 | 8    | 42.45 | 11.84 | 1.01 |
| 3           | 42.91 | 9.57 | 1.26 | 9    | 45.55 | 9.73 | 1.32 |
| 4           | 35.09 | 13.04 | 0.76 | 10   | 42.18 | 11.88 | 1 |
| 5           | 44.82 | 8.55 | 1.47 | 11   | 43.36 | 11.37 | 1.07 |
| 6           | 44.64 | 7.81 | 1.61 | 12   | 41.27 | 10.87 | 1.07 |
| 7           | 46.36 | 12.36 | 1.05 |       |       |       |       |

TABLE III shows fidelity reductions for trap caps 20 and 25 for 3 victim program lengths - 60, 80, and 100. For trap cap 20, the average fidelity reduction for these 3 program lengths are 2.71X, 5.66X, and 13.51X. For trap cap 25, the average fidelity reductions are 4.77X, 15.65X, and 68.13X. In case of trap cap 25, we observe aggravated fidelities, especially for larger victim sizes. Intuitively, this behavior can be attributed to the scaling factor $A$ in the gate fidelity equation $F = 1 - \Gamma \tau - A(2n+1)$. Factor $A \propto N/\log(N)$ where $N$ is the number of qubits in the chain. For larger victims in a larger capacity trap, $A$ scales up making the motional mode ($n$) more pronounced, and exacerbating gate fidelity ($F$).

2) Random attack: Table III shows the statistics for victim size sweep for random attack programs. The assumption of victim size 6 provides the best results in terms of ICV. Therefore, we select this program to launch future attacks.

B. Fidelity reduction

1) Systematic attack: Fig. 9 shows fidelity reduction of the victim program under attack for 3 victim lengths - 60, 80, and 100. The SC block length, trap cap, and assumed victim size are 80 gates, 15 ions, and 8 qubits respectively. The plot shows that the fidelity reduction increases with higher victim lengths. Average fidelity reductions are 2.63X, 5.40X, and 13.11X for victim lengths 60, 80, and 100 respectively. Fig. 10 qualitatively explains the positive correlation between victim length and fidelity reduction. The shuttle operations are spread across the length of the SC block. If the victim program completes before the SC block, shuttles at the later part of the block (hatched pattern in Fig. 10) does not affect the victim program. The opposite happens if the victim program is longer. Repeated shuttles from adversary programs increase the chain energy. Therefore, the later gates (cross pattern in Fig. 10) in the victim program experience excessive fidelity drops.

Table. III shows fidelity reductions for trap caps 20 and 25 for 3 victim program lengths - 60, 80, and 100. For trap cap 20, the average fidelity reduction for these 3 program lengths are 2.71X, 5.66X, and 13.51X. For trap cap 25, the average fidelity reductions are 4.77X, 15.65X, and 68.13X. In case of trap cap 25, we observe aggravated fidelities, especially for larger victim sizes. Intuitively, this behavior can be attributed to the scaling factor $A$ in the gate fidelity equation $F = 1 - \Gamma \tau - A(2n+1)$. Factor $A \propto N/\log(N)$ where $N$ is the number of qubits in the chain. For larger victims in a larger capacity trap, $A$ scales up making the motional mode ($n$) more pronounced, and exacerbating gate fidelity ($F$).

2) Random attack: Fig. 11 shows the fidelity reduction values for random attack program (trap cap = 15). We omit the values for trap cap 20 and 25 for brevity (fidelity reductions will be even higher at these capacities). The results show an average fidelity reduction of 2.22X, 4.0X, and 8.94X. These values are lower than the systematic attack.

C. Choice between systematic and random attack programs

The choice between systematic and random attack is not an either-or proposition although the systematic approach provides a higher fidelity reduction. The adversary needs to submit many programs to the cloud to find a good attack program using the random approach. Using the systematic approach, a good attack program can be generated in one try. Thus, the choice between approaches will depend on the resources available to the adversary. If he/she has information about the architectural policies, adopting the systematic approach is the fastest and the best choice. If an adversary has the resources to run many programs on the cloud (running programs will cost money) and/or does not have knowledge about necessary policies, then adopting the random approach will lead to stronger attacks.

VII. COUNTERMEASURES

A. Random initial mapping

The compiler can adopt a random initial mapping policy where each program at each iteration starts from a random allocation. Both malicious program creation methods rely on a consistent initial mapping i.e., the same program will be allocated in the same fashion for every run. In case of a random attack, if initial mapping changes randomly from one instance
Effective number of moves drastically drops to $\approx 27$ ($\sigma = 9.45$) (2.96X drop). Therefore, it proves the efficacy of random initial mapping in weakening the attack.

1) Trade-off of random initial mapping: Although a random initial mapping policy can disarm an adversary, it may penalize a legitimate user. A good initial mapping policy tries to place ions with frequent gates together so that communication can be minimized in typical benchmarks (note that attack programs are not typical programs– they are artificially crafted to contain numerous shuttles by hacking an intelligent initial mapping policy). However, a random initial mapping policy does not exploit such intelligence and cannot always guarantee an optimal number of communications. To show the impact of random mapping, we simulate a suite of popular noisy intermediate-scale quantum (NISQ) benchmarks used in [19] with both greedy and random mapping policies. Benchmarks include quantum Fourier transform (QFT), quantum approximation optimization algorithm (QAOA) circuit, supremacy circuit from Google’s quantum supremacy experiment, and quantum adder circuit. The circuits are generated using [44].

The mean values for random policy are computed from quantum adder circuit. The circuits are generated using [44]. circuit from Google’s quantum supremacy experiment, and approximation optimization algorithm (QAOA) circuit, supremacy include quantum Fourier transform (QFT), quantum approximation optimization algorithm (QAOA) circuit, supremacy circuit from Google’s quantum supremacy experiment, and quantum adder circuit. The circuits are generated using [44].

We find that with a random initial mapping policy, the average number of moves drastically drops to $\approx 27$ ($\sigma = 9.45$) (2.96X drop). Therefore, it proves the efficacy of random initial mapping in weakening the attack.

2) Hybrid approach: To alleviate the issue, the cloud can adopt a hybrid approach. In the hybrid approach, the compiler compiles a program with both random and intelligent (e.g., greedy) initial mapping and discards the result with higher shuttles. It will execute the version with the lower shuttles.

B. Dummy pad qubits in the victim program

A user (victim) can protect his/her program by adding a sufficient number of dummy qubits to pad the unused qubits in a trap. Suppose, the actual user program needs 10 qubits, and he/she wants to execute the program on a system with a trap cap 15/trap. In such a case, the user can add 5 dummy pad qubits in his/her program to make the program size 15 which will fully occupy a trap. Thus, an adversary qubit cannot share a trap with the victim preventing shuttle-induced fidelity degradation. The user can apply virtual-Z gates [45] (e.g., GZ gate in the IonQ machine [30]) on the dummy qubits. It will ensure that the compiler considers the qubits during allocation. As the virtual-Z gate is a software gate, it has perfect fidelity, requires no physical, and will not affect the user program.

However, there can be a security vs. cost trade-off. The quantum cloud may charge the user more for using more qubits. Consider a linear cost model where requesting 1 qubit cost 1 unit. The cost of running the 10-qubit will be 10 units. However, with 5 dummy qubits for padding and security, now the user has to spend 15 units increasing the cost by 1.5X. Not to mention that the cost model could be based on an exponential relation with the qubits counts. Therefore, this defense will be more cost-effective for a low number of dummy qubits (i.e., where actual user program size is large and/or trap cap is low).

C. Capping maximum number of allowed shuttles

The cloud can enforce a max shuttle to prevent shuttle-exploiting attacks. The cloud provider can check the required number of shuttles in a program, and if it exceeds the set maximum value, the cloud can schedule it separately (without any accompanying program). This means for certain programs the cloud will dynamically switch to a single-programming mode from the multi-programming mode. However, the cloud will lose some throughput due to this switching. It can cover the loss by charging extra for programs requiring a high number of shuttles. Suppose, the 18 qubit adversary program exceeds the max set shuttles. The cloud needs to run it in
a single-programming mode with 30 qubit resources (2 traps \times 15 qubits/trap). Thus, the cloud will now charge 30 units - considering the previous linear cost model - instead of 18 units before to cover the loss in device utilization. In this way, programs with high shuttles cannot affect other programs, and the cloud will not incur a loss.

VIII. CONCLUSION

In this paper, we present a vulnerability in multi-programming access to TI quantum computers and propose several defenses. The key takeaway message of the paper is to establish shuttle operations as a mode of attack. We also present several mitigation measures such as, hybrid mapping policy, padding user programs with dummy qubit, and setting a maximum allowed number of shuttles.

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