We present a methodology to price options and portfolios of options on a gate-based quantum computer using amplitude estimation, an algorithm which provides a quadratic speedup compared to classical Monte Carlo methods. The options that we cover include vanilla options, multi-asset options and path-dependent options such as barrier options. We put an emphasis on the implementation of the quantum circuits required to build the input states and operators needed by amplitude estimation to price the different option types. Additionally, we show simulation results to highlight how the circuits that we implement price the different option contracts. Finally, we examine the performance of option pricing circuits on quantum hardware using the IBM Q Tokyo quantum device. We employ a simple, yet effective, error mitigation scheme that allows us to significantly reduce the errors arising from noisy two-qubit gates.

I. INTRODUCTION

Options are financial derivative contracts that give the buyer the right, but not the obligation, to buy (call option) or sell (put option) an underlying asset at an agreed-upon price (strike) and timeframe (exercise window). In their simplest form, the strike price is a fixed value and the timeframe is a single point in time, but exotic variants may be defined on more than one underlying asset, the strike price can be a function of several market parameters and could allow for multiple exercise dates. As well as providing investors with a vehicle to profit by taking a view on the market or exploit arbitrage opportunities, options are core to various hedging strategies and as such, understanding their properties is a fundamental objective of financial engineering. For an overview of option types, features and uses, we refer the reader to Ref. [1].

Due to the stochastic nature of the parameters options are defined on, calculating their fair value can be an arduous task and while analytical models exist for the simplest types of options [2], the simplifying assumptions on the market dynamics required for the models to provide closed-form solutions often limit their applicability [3]. Hence, more often than not, numerical methods have to be employed for option pricing, with Monte Carlo being one of the most popular due to its flexibility and ability to generically handle stochastic parameters [4, 5]. However, despite their attractive features in option pricing, classical Monte Carlo methods generally require extensive computational resources to provide accurate option price estimates, particularly for complex options. Because of the widespread use of options in the finance industry, accelerating their convergence can have a significant impact in the operations of a financial institution.

By leveraging the laws of quantum mechanics a quantum computer [6] may provide novel ways to solve computationally intensive problems such as quantum chemistry [7–10], solving linear systems of equations [11], and machine learning [12–14]. Quantitative finance, a field with many computationally hard problems, may benefit from quantum computing. Recently developed applications of gate-based quantum computing for use in finance [15] include portfolio optimization [16], the calculation of risk measures [17] and pricing derivatives [18–20]. Several of these applications are based on the Amplitude Estimation algorithm [21] which can estimate a parameter with a convergence rate of $1/M$, where $M$ is the number of quantum samples used. This represents a theoretical quadratic speed-up compared to classical Monte Carlo methods.

In this paper we extend the pricing methodology presented in [17, 18] and place a strong emphasis on the implementation of the algorithms in a gate-based quantum computer. We first classify options according to their features and show how to take the different features into account in a quantum computing setting. In Section III, we review the quantum algorithms needed to price options and discuss how to represent relevant probability distributions in a quantum computer. In Section IV, we show a framework to price vanilla options and portfolios of vanilla options, options with path-dependent payoffs and options on several underlying assets. In Section V we show results from evaluating our option circuits on quantum hardware, and describe the error mitigation scheme we employ to increase the accuracy of the estimated option prices. In particular, we employ the maximum likelihood estimation method introduced in [22] to perform amplitude estimation without phase estimation in option pricing using three qubits of a real quantum device.

II. REVIEW OF OPTION TYPES AND THEIR CHALLENGES

We classify options according to two categories: path-independent vs path-dependent and options on single assets or on multiple assets. Path-dependent options have a payoff function that depends on an underlying asset at a single point in time. Therefore, the price of the asset
up to the exercise date of the option is irrelevant for the option price. By contrast, the payoff of path-dependent options depends on the evolution of the price of the asset and its history up to the exercise date. Table I exemplifies this classification. Options that are path-independent and rely on a single asset are the easiest to price. This is done using Amplitude Estimation once a proper representation of the distribution of the underlying asset can be loaded to the quantum computer. Path-independent options on multiple assets are only slightly harder to price since more than one asset is now involved and the probability distribution loaded into the quantum computer must account for correlations between the assets. Path-dependent options are harder to price than path-independent options since they require a representation of the possible paths the underlying assets can take in the quantum computer.

### III. IMPLEMENTATION ON A GATE BASED QUANTUM COMPUTER

Here we review some of the building blocks needed to price options on a gate-based quantum computer.

#### A. Distribution loading

The analytical formulas used to price options in the Black-Scholes-Merton (BSM) model [2, 23] assume that the underlying stock prices at maturity follow a lognormal distribution with constant volatility. Such distributions can be efficiently loaded in a gate-based quantum computer [18, 24]. However, to properly model the market prices of options, the volatility of the geometric brownian process describing the evolution of the assets must be changed for options with different strike prices [25]. This discrepancy between the BSM model and market prices is because stocks do not follow a geometric Brownian motion process with constant volatility. It is thus important to be able to efficiently represent arbitrary distributions of financial data in a quantum computer.

The loading of arbitrary states into quantum systems requires exponentially many gates [26], making it inefficient to model arbitrary distributions as quantum gates. Since the distributions of interest are often of a special form, the limitation may be overcome by using Quantum Generative Adversarial Networks (qGAN). These networks allow us to load a distribution using a polynomial number of gates [19]. A qGAN can learn the random distribution $X$ underlying the observed data samples $\{x^0, \ldots, x^{k-1}\}$ and load it directly into a quantum state. This generative model employs the interplay of a classical discriminator, a neural network [27], and a quantum generator (a parametrized quantum circuit). More specifically, the qGAN training consists of alternating optimization steps of the discriminator’s parameters $\phi$ and the generator’s parameters $\theta$. After the training, the output of the generator is a quantum state

$$\psi(\theta) = \sum_{i=0}^{2^n-1} \sqrt{p_i(\theta)} |i\rangle_n,$$

that represents the target distribution. The $n$-qubit state $|i\rangle_n = |i_{n-1} \ldots i_0\rangle$ encodes the integer $i = 2^{n-1}i_{n-1} + \ldots + 2i_1 + i_0 \in \{0, \ldots, 2^n - 1\}$ with $i_k \in \{0, 1\}$ and $k = 0, \ldots, n - 1$. The probabilities $p_i(\theta)$ approximate the random distribution underlying the training data. We note that the outcomes of a random variable $X$ can be mapped to the integer set $\{0, \ldots, 2^n - 1\}$ using an affine mapping. Furthermore, the approach can be easily extended to multivariate data, where we use a separate register of qubits for each dimension [19].

#### B. Amplitude Estimation

The advantage of pricing options on a quantum computer comes from the amplitude estimation (AE) algorithm [21] which provides a quadratic speed-up over classical Monte-Carlo simulations [28, 29]. Suppose a unitary operator $A$ acting on a register of $(n + 1)$ qubits such that

$$A |0\rangle_{n+1} = \sqrt{1 - a} |\psi_0\rangle_n |0\rangle + \sqrt{a} |\psi_1\rangle_n |1\rangle$$

for some normalized states $|\psi_0\rangle_n$ and $|\psi_1\rangle_n$, where $a \in [0, 1]$ is unknown. AE allows the efficient estimation of $a$, i.e., the probability of measuring $|1\rangle$ in the last qubit. This estimation is obtained with an operator $Q$, based on $A$, and Quantum Phase Estimation [30] to approximate

![FIG. 1. The quantum circuit of amplitude estimation, where $H$ denotes a Hadamard gate and $F^\dagger$ the inverse QFT.](image-url)
Here, the independent variable \( i = 4k + 2n + i_0 \in \{0, ..., 7\} \) is encoded by three qubits in the state \( |i⟩_1 |i⟩_2 |i⟩_3 \) with \( i_k \in \{0, 1\} \). Therefore, the linear function \( f(i) = f_1 i + f_0 \) is given by \( 4f_1 i_2 + 2f_1 i_1 + f_1 i_0 + f_0 \). After applying this circuit the quantum state is \( |i⟩_1 |i⟩_2 |i⟩_3 |0⟩ \cos(f_1 i + f_0) |0⟩ + \sin(f_1 i + f_0) |1⟩ \). The circuit on the right shows an abbreviated notation.

We can efficiently create an operator that performs \( \{ \{ f(i) \} \} \equiv |i⟩_1 |i⟩_2 |i⟩_3 |0⟩ \cos(f(i)) |0⟩ + \sin(f(i)) |1⟩ \).

Using the procedure outlined in Sec. III C. The parameter \( c \in [0, 1] \) is a scaling parameter. The functions \( f(i) \) and \( \tilde{f}(i) \) are related by

\[
\tilde{f}(i) = \frac{2}{f_{\max} - f_{\min}} f(i) - f_{\min} - 1.
\]

Here \( f_{\min} = \min_i f(i) \) and \( f_{\max} = \max_i f(i) \). The relation in Eq. (5) is chosen so that \( f(i) \in [-1, 1] \).

We obtain the expectation value of a linear function \( f \) of a random variable \( X \) with AE by creating the operator \( A \) such that \( a = \mathbb{E}[f(X)] \), see Eq. (2). Once \( A \) is implemented we can prepare the state in Eq. (2) and the \( Q \) operator. In this section, we show how to create a close relative of the operator in Eq. (2) and then, in Section III D, we show how to use AE.

Since the payoff function for option portfolios is piecewise linear we only need to consider linear functions \( f : \{0, ..., 2^n - 1\} \rightarrow [0, 1] \) which we write \( f(i) = f_1 i + f_0 \). We can efficiently create an operator that performs

\[
|i⟩_n \rightarrow |i⟩_n (\cos(f(i)) |0⟩ + \sin(f(i)) |1⟩)
\]

using controlled Y-rotations [17]. To implement the linear term of \( f(i) \) each qubit \( j \) (where \( j \in \{0, ..., n - 1\} \)) in the \( |i⟩_n \) register acts as a control for a Y-rotation with angle \( 2f_1 \) of the ancilla qubit. The constant term \( f_0 \) is implemented by a rotation of the ancilla qubit without any controls, see Fig. 2. The controlled Y-rotations can be implemented with CNOT and single-qubit gates [32].

C. Linearly controlled Y-rotations

We obtain the expectation value of a linear function \( f \) of a random variable \( X \) with AE by creating the operator \( A \) such that \( a = \mathbb{E}[f(X)] \), see Eq. (2). Once \( A \) is implemented we can prepare the state in Eq. (2) and the \( Q \) operator. In this section, we show how to create a close relative of the operator in Eq. (2) and then, in Section III D, we show how to use AE.

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D. Expectation value of functions using AE

We now describe how to obtain \( \mathbb{E}[f(X)] \) for a linear function \( f \) of a random variable \( X \) which is mapped to integer values \( i \in \{0, ..., 2^n - 1\} \) that occur with probability \( p_i \). To do this we create the operator that maps \( \sum_i \sqrt{p_i} |i⟩_n \rightarrow |0⟩ \cos(f(i)) |0⟩ + \sin(f(i)) |1⟩ \). Using the procedure outlined in Sec. III C. The parameter \( c \in [0, 1] \) is a scaling parameter. The functions \( f(i) \) and \( \tilde{f}(i) \) are related by

\[
\tilde{f}(i) = \frac{2}{f_{\max} - f_{\min}} f(i) - f_{\min} - 1.
\]

Here \( f_{\min} = \min_i f(i) \) and \( f_{\max} = \max_i f(i) \). The relation in Eq. (5) is chosen so that \( f(i) \in [-1, 1] \). Thus, \( \sin^2[c\tilde{f}(i) + \pi/4] \) is an anti-symmetric function around \( \tilde{f}(i) = 0 \). With these definitions, the probability to find the ancilla qubit in state \( |1⟩ \) namely

\[
P_1 = \sum_{i=0}^{2^n - 1} p_i \sin^2 \left( c\tilde{f}(i) + \frac{\pi}{4} \right),
\]

is well approximated by

\[
\sum_{i=0}^{2^n - 1} p_i \left( c\tilde{f}(i) + \frac{1}{2} \right) = c - \frac{2\mathbb{E}[f(X)] - f_{\min} - f_{\max} - c}{f_{\max} - f_{\min} - c + 1/2}.
\]

To obtain this result we made use of the approximation

\[
\sin^2 \left( c\tilde{f}(i) + \frac{\pi}{4} \right) = c\tilde{f}(i) + \frac{1}{2} + O(c^3 \tilde{f}(i))
\]

which is valid for small values of \( c\tilde{f}(i) \). With this first order approximation the convergence rate of AE is \( O(M^{-2/3}) \) when \( c \) is properly chosen which is already faster than classical Monte Carlo methods [17]. We can recover the \( O(M^{-1}) \) convergence rate of AE by using higher orders implemented with quantum arithmetic. The resulting circuits, however, have more gates. This trade-off, discussed in Ref. [17], also gives a formula that specifies which value of \( c \) to use to minimize the estimation error made when using AE. From Eq. (6) we can recover \( \mathbb{E}[f(X)] \) since AE allows us to efficiently retrieve \( P_1 \) and because we know the values of \( f_{\min}, f_{\max} \) and \( c \).

IV. OPTION PRICING ON A QUANTUM COMPUTER

In this section we show how to price the different options shown in Tab. I. We put an emphasis on the implementation of the quantum circuits that prepare the states needed by AE. We use the different building blocks reviewed in Sec. III.
A. Path-independent options

The price of path-independent vanilla options (e.g., European call and put options) depend only on the distribution of the underlying asset price \( S_T \) at the option maturity \( T \) and the payoff function \( f(S_T) \) of the option. To encode the distribution of \( S_T \) in a quantum state we truncate it to the range \([S_{T,\min}, S_{T,\max}]\) and discretize this interval to \( \{0,...,2^n-1\} \) using \( n \) qubits. In the quantum computer the distribution loading operator \( P_X \) creates a state

\[
|0\rangle_n P_X |\psi\rangle_n = \sum_{i=0}^{2^n-1} \sqrt{p_i} |i\rangle_n,
\]

with \( i \in \{0,...,2^n-1\} \) to represent \( S_T \). This state, exemplified in Fig. 3, may be created using the methods discussed in Sec. III A.

We start by showing how to price vanilla call or put options and then generalize our method to capture the payoff structure of portfolios containing more than one vanilla option.

\[ \text{FIG. 3. Example price distribution at maturity loaded in a three-qubit register. In this example we followed the Black-Scholes-Merton model which implies a lognormal distribution of the asset price at maturity } \ T \text{ with probability density function } P(S_T) = \frac{1}{S_T \sigma \sqrt{2 \pi T}} \exp \left( -\frac{\ln(S_T - \mu)^2}{2 \sigma^2 T} \right). \text{ } \sigma \text{ is the volatility of the asset and } \mu = (r - 0.5 \sigma^2) T + \ln(S_0), \text{ with } r \text{ the risk-free market rate and } S_0 \text{ the asset’s spot at } t = 0. \text{ In this figure we used } S_0 = 2, \sigma = 10\%, r = 4\% \text{ and } T = 300/365. \]

1. Vanilla options

To price vanilla options with strike \( K \), we implement a comparison between the values in state (8) with \( K \). A quantum comparator circuit sets an ancilla qubit \( |c\rangle \), initially in state \( |0\rangle \), to the state \( |1\rangle \) if \( i \geq K \) and \( |0\rangle \) otherwise. The state \( |\psi\rangle_n \) in the quantum computer therefore undergoes the transformation

\[
|\psi\rangle_n |0\rangle \rightarrow |\phi_1\rangle = \sum_{i<K} \sqrt{p_i} |i\rangle_n |0\rangle + \sum_{i\geq K} \sqrt{p_i} |i\rangle_n |1\rangle.
\]

This operation can be implemented by a quantum comparator [33] based on CNOT and Toffoli gates. Since we know the value of the strike, we can implement a circuit tailored to the specific strike price. We use \( n \) ancilla qubits \( |a_1,...,a_n\rangle \) and compute the two’s complement of the strike price \( K \) in binary using \( n \) bits, storing the digits in a classical array \( t[n] \). For each qubit \( |i_k\rangle \) in the \( |\psi\rangle_n \) register, with \( k \in \{0,...,n-1\} \), we compute the possible carry bit of the bitwise addition of \( |i_k\rangle \) and \( t[k] \) into \( |a_k\rangle \). If \( t[k] = 0 \), there is a carry qubit at position \( k \) only if there is a carry at position \( k - 1 \) and \( |i_k\rangle = 1 \). If \( t[k] = 1 \), there is a carry qubit at position \( k \) if there is a carry at the last (most significant) qubit. This procedure along with the necessary gate operations is illustrated in Fig. 4. An implementation for \( K = 1.9 \) and a three-qubit register is shown in Fig. 6.

To prepare the operator for use with AE we add to \( |\phi_1\rangle \) a second ancilla qubit initially in the state \( \cos(g_0) |0\rangle + \sin(g_0) |1\rangle \). Here, \( g_0 \) is an angle with a value that we will carefully select. Next, we perform a rotation of the new ancilla qubit controlled by the comparator qubit \( |c\rangle \) and the qubits in \( |\psi\rangle_n \). The state \( |\phi_1\rangle \) \( \{\cos(g_0) |0\rangle + \sin(g_0) |1\rangle \} \) is mapped to

\[
\sum_{i<K} \sqrt{p_i} |i\rangle_n |0\rangle \{\cos(g_0) |0\rangle + \sin(g_0) |1\rangle \} + \sum_{i\geq K} \sqrt{p_i} |i\rangle_n |1\rangle \{\cos(g_0 + g(i)) |0\rangle + \sin(g_0 + g(i)) |1\rangle \}.
\]

This operation, implemented by the quantum circuit in Fig. 7, applies a rotation with an angle \( g(i) \) only if \( i \geq K \). The probability to find the second ancilla in state \( |1\rangle \), efficiently measurable using AE, is

\[
P_1 = \sum_{i<K} p_i \sin^2(g_0) + \sum_{i\geq K} p_i \sin^2(g_0 + g(i)).
\]

Now, we must carefully chose the angle \( g_0 \) and the function \( g(i) \) to recover the expected payoff \( \mathbb{E}[f(X)] \) of the option from \( P_1 \) using the approximation in Eq. (6). The payoff function of vanilla options is piece-wise linear

\[
f(i) = \begin{cases} a_c \cdot i + b_c & i < K, \\ a_\ge \cdot i + b_\ge & i \geq K. \end{cases}
\]

We now focus on a European call option with payoff \( f(i) = \max(0, i - K) \), i.e., \( a_c = b_c = 0 \), \( a_\ge = 1 \), and \( b_\ge = -K \). To reproduce \( f(i) = i - K \) for \( i \geq K \) and simultaneously satisfy \( g_0 + g(i) - \pi/4 \in [-c, c] \), see Sec. III D, we must set

\[
g(i) = \frac{2c(i-K)}{i_{\text{max}} - K},
\]
FIG. 4. Circuit that compares the value represented by an n-qubit register $|i\rangle^n$, to a fixed value $K$. We use $n$ ancilla qubits $|a_1\rangle, \ldots, |a_n\rangle$, a classical array $t[n]$ holding the precomputed binary value of $K$’s two’s complement and a qubit $|c\rangle$ which will hold the result of the comparison with $|c\rangle = 1$ if $|i\rangle \geq K$. For each qubit $|a_k\rangle$, with $k \in \{1, \ldots, n\}$, we use a Toffoli gate to compute the carry at position $k$ if $t[k] = 1$ and a logical OR, see Fig. 5, if $t[k] = 0$. For $k = 1$, we only need to use a CNOT on $|i\rangle$ if $t[1] = 1$. In the circuit above, only one of two unitaries in a dotted box needs to be added to the circuit, depending on the value of $t[k]$ at each qubit. The last carry qubit $|a_n\rangle$ is then used to compute the final result of the comparison in qubit $|c\rangle$.

FIG. 5. Circuit that computes the logical OR between qubits $|a\rangle$ and $|b\rangle$ into qubit $|c\rangle$. The circuit on the right shows the abbreviated notation used in Fig. 4.

FIG. 6. Quantum circuit that sets a comparator qubit $|c\rangle$ to $|1\rangle$ if the value represented by $|i\rangle^n$ is larger than a strike $K = 1.9$, for the spot distribution in Fig. 3. The unitary $P_X$ represents the set of gates that load the probability distribution in Eq. (8). An ancilla qubit $|a\rangle$ is needed to perform the comparison. It is uncomputed at the end of the circuit.

where $i_{\text{max}} = 2^n - 1$. This choice of $g(i)$ forces us to chose

$$g_0 = \frac{\pi}{4} - c. \quad (13)$$

To see why, we substitute Eqs. (12) and (13) in Eq. (10) and use the approximation in Eq. (7). Therefore,

$$P_1 \approx \sum_{i < K} p_i \left( -\frac{1}{2} - c \right) + \sum_{i \geq K} p_i \left( \frac{2c(i - K)}{i_{\text{max}} - K} + \frac{1}{2} - c \right)$$

$$= \frac{1}{2} - c + \frac{2c}{i_{\text{max}} - K} \sum_{i \geq K} p_i (i - K). \quad (14)$$

This shows us that we needed $g_0 = \pi/4 - c$ to used the identity $\sum_i p_i = 1$ to recover $\mathbb{E}\{\max(0, i - K)\}$ up to a scaling factor and a constant. From this last equality we recover the expected payoff of the option given the probability distribution of the underlying asset. We should note that the fair value of the option requires appropriately discounting the expected payoff of the option to today, but as the discounting can be performed after the expectation value has been calculated we omit it from our discussion for simplicity. We demonstrate the
Various popular trading and hedging strategies rely on entering multiple option contracts at the same time instead of individual call or put options and as such, these strategies allow an investor to effectively construct a payoff that is more complex than that of vanilla options. For example, an investor that wants to profit from a volatile asset without picking a direction of where the volatility may drive the asset’s price, may choose to enter a straddle option strategy, by buying both a call and a put option on the asset with the same expiration date and strike. If the underlying asset moves sharply up to expiration date, the investor can make a profit regardless of whether it moves higher or lower in value. Alternatively, the investor may opt for a butterfly option strategy by entering four appropriately structured option contracts with different strikes simultaneously. Because these option strategies give rise to piecewise linear payoff functions, the methodology described in the previous section can be extended to calculate the fair values of these option portfolios.

In order to capture the structure of such option strategies, we can think of the individual options as defining one or more effective strike prices $K_j$ and add a linear function $f_j(S) = a_j S + b_j$ between each of these strikes. For example, to price an option strategy with the payoff function

$$f_S(S) = \max(0, S - K_1) - \max(0, S - K_2), \quad (15)$$

which corresponds to a call spread (the option holder has purchased a call with strike $K_1$ and sold a call with strike $K_2$), we use the functions $f_0$, $f_1$, and $f_2$ such that

$$f_S(S) = \begin{cases} f_0(S) & S < K_1, \\ f_0(S) + f_1(S) & K_1 \leq S < K_2, \\ f_0(S) + f_1(S) + f_2(S) & K_2 \leq S. \end{cases} \quad (16)$$

To match Eq. (15) with Eq. (16) we set $f_0(S) = 0$, $f_1(S) = S - K_1$ and $f_2(S) = -S + K_2$. In general, to price a portfolio of options with $m$ effective-strike prices $K_1, \ldots, K_m$ and $m+1$ functions $f_0(S), \ldots, f_m(S)$ we need an ancilla qubit per strike to indicate if the underlying has reached the strike. This allows us to generalize the discussion from Sec. IV A 1. We apply a multi-controlled Y-rotation with angle $g_j(i)$ if $i \geq K_j$ for each strike $K_j$ with $j \in \{1, \ldots, m\}$. The rotation $g_0(i)$ is always applied, see the circuit in Fig. 9. The functions $g_j(i)$ are determined using the same procedure as in Sec. IV A 1.

### B. Multi-asset and path-dependent options

In this section we show how to price options with path-dependent payoffs as well as options on more than one underlying asset. In these cases, the payoff function depends on a multivariate distribution of random variables $\{S_j\}$ with $j \in \{1, \ldots, d\}$. The $S_j$’s may represent one or several assets at discrete moments in time or a basket of assets at the option maturity. In both cases, the probability distribution of the random variables $S_j$ are truncated to the interval $[S_{j,\text{min}}, S_{j,\text{max}}]$ and discretized using

### 2. Portfolios of options

A straightforward extension of the analysis above yields a pricing model for a European put option, whose payoff $f(i) = \max(0, K - i)$ is equivalent to Eq. (11) with $a_\geq = b_\geq = 0$, $a_\leq = -1$, and $b_\leq = K$.

![Graph](image-url)
The previous section to encode the option payoffs into the computation in-place to minimize the number of qubit operations or basket options, require us to compute the sum of the random variables \( \sum_{n} \phi \). Various types of options, such as Asian options or basket options, need to be evaluated. In quantum computers, this is typically achieved using adder circuits based on CNOT and Toffoli gates [35–37]. To this end we add an extra qubit register with \( n \) qubits to serve as an accumulator. By recursively applying adder circuits we transform the transformation \( |\psi\rangle_n = \sum_{i_1, \ldots, i_d} \sqrt{P_{i_1, \ldots, i_d}} |i_1\rangle_{n_1} \otimes \cdots \otimes |i_d\rangle_{n_d} \) with \( n = \sum_j n_j \).

A European style basket option is an extension of the single asset European option discussed in Sec. IVA. Only now the payoff depends on a weighted sum of \( d \) underlying assets. A call option on a basket has the payoff profile

\[ f(S_{\text{basket}}) = \max(0, S_{\text{basket}} - K) \]

FIG. 9. Quantum circuit that implements the multi-controlled Y-rotations for a portfolio of options with \( m \) strike prices.

\[ |\hat{i}_n \rangle, |c_m \rangle, \ldots, |c_2 \rangle, |c_1 \rangle \]

\[ |0\rangle \to [R_y(g_0(i)) | R_y(g_1(i)) | R_y(g_2(i)) \cdots | R_y(g_m(i))] \]

where \( S_{\text{basket}} = \sum_{i=1}^{d} w_i \cdot \bar{S}_i \) for basket weights \( w_i = [w_{1, w_2, \ldots, w_d}] \) with \( w_i \in [0, 1] \), underlying asset prices at option maturity \( \bar{S} = [S_1, S_2, \ldots, S_d] \) and strike \( K \). In the BSM model, the underlying asset prices are described by a multivariate lognormal distribution with probability density function [38]

\[ P(\bar{S}) = \exp \left( -\frac{1}{2} (\ln S - \mu)^T \Sigma^{-1} (\ln S - \mu) \right) \frac{1}{(2\pi)^{d/2} (\det \Sigma)^{1/2}} \prod_{i=1}^{d} S_i \]

where \( \ln S = (\ln S_1, \ln S_2, \ldots, \ln S_d)^T \) and \( \mu = (\mu_1, \mu_2, \ldots, \mu_d)^T \), where each \( \mu_i \) is the lognormal distribution parameter for each asset defined in the caption of Fig. 3. \( \Sigma \) is the \( d \times d \) positive-definite covariance matrix of the \( d \) underlyings

\[ \Sigma = T \begin{bmatrix} \sigma_1^2 & \rho_{12} \sigma_1 \sigma_2 & \cdots & \rho_{1d} \sigma_1 \sigma_d \\ \rho_{21} \sigma_1 \sigma_2 & \sigma_2^2 & \cdots & \rho_{2d} \sigma_2 \sigma_d \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{d1} \sigma_1 \sigma_d & \cdots & \cdots & \sigma_d^2 \end{bmatrix} \]

with \( \sigma_i \) the volatility of the \( i \)th asset, \(-1 \leq \rho_{ij} \leq 1\) the correlation between assets \( i \) and \( j\) and \( T \) the time to maturity.

The quantum circuit for pricing a European style basket call option is analogous to the single asset case, with an additional unitary to compute the weighted sum of the uncertainty registers \( |i_1\rangle_{n_1} \cdots |i_d\rangle_{n_d} \) before applying the comparator and payoff circuits, controlled by the accumulator register \( |b\rangle_{n'} = |i_1 + \cdots + i_d\rangle_{n'} \). A schematic of these components is shown in Fig. 10. The implementation details of the circuit that performs the weighted sum operator is discussed in Appendix A.

We use a basket option to compare the estimation accuracy between AE and classical Monte Carlo. For \( M \) applications of the \( Q \) operator, see Fig. 1, the possible values returned by AE will be of the form \( \sin^2(\pi y/M) \) for \( y \in \{0, ..., M-1\} \) and the maximum distance between two consecutive values is

\[ \Delta_{\text{max}} = \sin^2 \left( \frac{\pi}{4} + \frac{2\pi}{4M} \right) - \sin^2 \left( \frac{\pi}{4} - \frac{2\pi}{4M} \right) \]

This quantity determines how close \( M \) operations of \( Q \) can get us to the amplitude which encodes the option price. Using \( \sin^2(\pi/4+x) = x+1/2+O(x^3) \) for \( x \ll 1 \), we get \( \Delta_{\text{max}} = \pi/M + O(M^{-3}) \) for \( \pi/M \ll 1 \). From Eq. (3) and Eq. (14) we can determine that with probability of at least \( 8/\pi^2 \), our estimated option price using AE will be within

\[ \Delta_{\text{max}} = \frac{\pi/M}{2c} \times (i_{\text{max}} - K) + O(M^{-3}) \]

of the exact option price, where \( c, i_{\text{max}} \) and \( K \) are the parameters used to encode the option payoff into our quantum circuit, discussed in Sec. IV A1. To compare this estimation error to Monte Carlo, we use the same number
Specifically, the payoff of an Asian call option is given by

\[
f(b) = \max(0, b - K)
\]

where \(K\) is the strike price, \(\bar{S}\) is the arithmetic average of the asset’s value over a pre-defined number of points \(d\) between 0 and the option maturity \(T\)

\[
\bar{S} = \frac{1}{d} \sum_{t=1}^{d} S_t.
\]

The probability distribution of asset prices at time \(t\) will again be lognormal with probability density function

\[
P(S_t) = \frac{1}{S_t \sigma \sqrt{2\pi \Delta t}} e^{-\frac{(\ln S_t - \mu t)^2}{2\sigma^2 \Delta t}}
\]

with \(\mu_t = (r - 0.5 \sigma^2) \Delta t + \ln(S_{t-1})\) and \(\Delta t = T/d\). We can then use the multivariate distribution in Eq. (20), with \(\bar{S}\) now a \(d\)-dimensional vector of asset prices at time points \([t_1 \ldots t_d]\), instead of distinct underlying prices at maturity \(T\). As we are not considering multiple underlying assets that could be correlated, the covariance matrix is diagonal \(\Sigma = \Delta t \text{diag}(\sigma^2, \ldots, \sigma^2)\). An illustration of the probability density function used for an asset defined on two time steps is shown in Fig. 12.

We now prepare the state \(|\psi\rangle_n\), see Eq. (17), where each register represents the asset price at each time step up to maturity. Using the weighted sum operator of Appendix A with equal weights \(1/d\), we then calculate the average value of the asset until maturity \(T\), see Eq. (25), into a register \(|\bar{S}\rangle\)

\[
|i_1, i_2, \ldots, i_d\rangle \rightarrow |\bar{S}\rangle = \frac{1}{d} \sum_{t=1}^{d} S_t.
\]

Finally, we use the same comparator and rotation circuits that we employed for the basket option illustrated in Fig. 10 to load the payoff of an arithmetic average Asian option into the payoff qubit \(|p\rangle\).

3. Barrier Options

Barrier options are another class of popular option types whose payoff is similar to vanilla European Op-
tions, but they become activated or extinguished if the underlying asset crosses a pre-determined level called the barrier. In their simplest form, there are two general categories of barrier options

- **Knock-Out**: The option expires worthless if the underlying asset crosses a certain price level before the option’s maturity.

- **Knock-In**: The option has no value unless the underlying asset crosses a certain price level before maturity.

If the required barrier event for the option to have value at maturity occurs, the payoff then depends only on the value of the underlying asset at maturity and not on the path of the asset until then. If we consider a Knock-In barrier option and label the barrier level \( B \), we can write the option’s payoff as

\[
f(S) = \begin{cases} 
\max(0, S_T - K) & \text{if } \exists \text{ s.t. } S_t \geq B \\
0 & \text{otherwise} 
\end{cases} \quad (28)
\]

where \( T \) is the time to maturity, \( S_t \) the asset price at time \( t \) with \( 0 < t \leq T \) and \( K \) the option strike.

To construct a quantum circuit to price a Knock-In barrier option, we use the same method as for the Asian option where \( T \) is divided into \( d \) equidistant time intervals with \( \Delta t = T/d \), and use registers \( |i_1\rangle_{n_1} |i_2\rangle_{n_2} \ldots |i_d\rangle_{n_d} \) to represent the discretized range of asset prices at time \( t \in \{\Delta t, 2\Delta t, \ldots, d \cdot \Delta t = T\} \). The probability distribution of Eq. (26) is used again to create the state \( |\psi\rangle_n \) in Eq. (17).

To capture the path dependence introduced by the barrier, we use an additional \( d \)-qubit register \( |b\rangle_d \) to monitor if the barrier is crossed. Each qubit \( |b_i\rangle \) in \( |b\rangle_d \) is set to \( |1\rangle \) if \( |i_i\rangle_{n_i} \geq B \). An ancilla qubit \( |b_i\rangle \) is set to \( |1\rangle \) if the barrier has been crossed in at least one time step. This is done by computing the logical OR, see Fig. 5, of every qubit in \( |b\rangle_d \) and storing the result in the ancilla

\[
|b_1 b_2 \ldots b_d\rangle |0\rangle \rightarrow |b_1 b_2 \ldots b_d\rangle |b_1 \| b_2 \| \ldots \| b_d\rangle. \quad (29)
\]

This is computed with \( X \) (NOT) and Toffoli gates and \( d-2 \) ancilla qubits. The ancilla qubit \( |b_i\rangle \) is then used as a control for the payoff rotation into the payoff qubit, effectively knocking the option in. For Knock-Out barrier options, we can follow the same steps and apply an \( X \) gate to the ancilla barrier qubit before using it as control, in this manner knocking the option out if the barrier level has been crossed. A circuit displaying all the components required to price a Knock-In barrier option is shown in Fig. 13. Results from amplitude estimation on a barrier option circuit using a quantum simulator are shown in Fig. 14.

Even though we have focused our attention on barrier options where the barrier event is the underlying asset crossing a barrier from below, we can use the same method to price barrier options where barrier events are defined as the asset crossing the value from above. This only requires changing the comparator circuits to compute \( S_t \leq B \) in the barrier register \( |b\rangle_d \).

\section{V. Quantum Hardware Results}

In this section we show results for a European call option evaluated on quantum hardware. We use three qubits, two of which represent the uncertainty and one encodes the payoff.

We consider a log-normal random distribution with \( S_0 = 2 \), \( \sigma = 40\% \), \( r = 5\% \), and \( T = 40/365 \), see Fig. 3, and truncate the distribution to the interval defined by three standard deviations around the mean. With two qubits encoding this distribution, the possible values are \([1.21, 1.74, 2.28, 2.81] \), represented by \(|00\rangle, \ldots, |11\rangle \), with corresponding probabilities 0.1\%, 55.4\%, 42.5\%, and 1.9\%. We set the strike price to \( K = 1.74 \).

To examine the behavior of the circuit for different input probability distributions, we run eight experiments that differ by the initial spot price \( S_0 \) and all other parameters are kept constant. The spot price is varied from 1.8 to 2.5 in increments of 0.1. This way we can use the same circuit for all experiments and only vary the Y-rotation angles used to map the initial probability distribution onto the qubit register. This choice of input parameters allows us to evaluate our circuits for expected option prices in the range \([0.0754, 0.7338]\).

Each experiment is evaluated on the IBM Q Tokyo 20-qubit device with 8192 shots. We repeat each 8192-shot experiment 20 times and average over the 20 measured probabilities in order to limit the effect of any one-off issues with the device. The standard deviation of the measured probabilities across the 20 runs was always \(< 2\% \).

The connectivity of IBM Q Tokyo allows to choose three fully connected qubits for the experiments, and thus, no
swaps are required to implement any two-qubit gate in our circuits [34]. For all circuits described in the following sections, we used qubits 6, 10 and 11.

**A. Algorithm and Operators**

We now show how to construct the operator $\mathcal{A}$ that is required for AE. The log-normal distribution on two qubits can be loaded using a single CNOT gate and four single qubit rotations [39]. To encode the payoff function we also exploit the small number of qubits and apply a uniformly controlled Y-rotation instead of the generic construction using comparators introduced in Sec. IV. A uniformly controlled Y-rotation, i.e.

$$|i\rangle_n |0\rangle \rightarrow |i\rangle_n R_y(\theta_i) |0\rangle ,$$

implements a different rotation angle $\theta_i$, $i = 0, \ldots, 2^n - 1$ for each state of the $n$-control qubits. For $n = 2$, this operation can be efficiently implemented using four CNOT gates and four single qubit Y-rotations [40, 41]. The resulting circuit implementing $\mathcal{A}$ is shown in Fig. 15. Note that in our setup different initial distributions only lead to different angles of the first four Y-rotations and do not affect the rest of the circuit. Although we use a uniformly controlled rotation, the rotation angles are constructed in the same way described in Sec. IIIID. We use an approximation scaling of $c = 0.25$ and the resulting angles are $[\theta_0, \ldots, \theta_3] = [1.1781, 1.1781, 1.5708, 1.9635]$, which shows the piecewise linear structure of the payoff function.

The total resulting circuit requires five CNOT gates and eight single-qubit Y-rotations, see Fig. 15. Since we use uniformly controlled rotations, we do not need any ancilla qubit. Note that if we want to evaluate the circuit for $\mathcal{A}$ alone, we can replace the last CNOT gate in Fig. 15 by classical post-processing of the measurement result: if $q_1$ is measured as $|1\rangle$, we flip $q_2$ and otherwise we do nothing. This further reduces the overall CNOT gate count to four.

A quadratic speed-up can also be realized by performing AE without quantum phase estimation [22]. This is done by measuring $Q^k \mathcal{A} |0\rangle$ for $k = 2^0, \ldots, 2^{m-1}$ for a given $m$ and applying a maximum likelihood estimation. If we define $M = 2^m - 1$, i.e. the total number of $\mathcal{Q}$-applications, and we consider $N$ shots for each experi-
Evaluating payoff function

\[ E_{\text{payoff}} = R_q \cdot R_y \cdot R_y \cdot \ldots \cdot R_y \]

\[ \text{Loading random distribution} \]

\[ \text{Evaluating payoff function} \]

FIG. 15. The \( A \) operator of the considered European call option: first, the 2-qubit approximation of a log-normal distribution is loaded, and second, the piecewise linear payoff function is applied to last qubit controlled by the first two. This operator can be used within amplitude estimation to evaluate the expected payoff of the corresponding option.

B. Error mitigation and results

We run the circuits for \( A \{0\}_3 \) and \( QA\{0\}_3 \) on noisy quantum hardware. The results are affected by readout errors and errors that occur during the execution of the circuits.

To mitigate readout errors we run a calibration sequence in which we individually prepare and measure all eight basis states \([34, 42]\). The result is a \( 8 \times 8 \) readout matrix \( R \) that holds the probability of measuring each basis state as function of the basis state in which the system was prepared. We use \( R \) to correct all subsequent measurements. The error we measure on \( P_1 \) for \( A \{0\}_3 \) was reduced from \( \sim 6\% \) to \( \sim 4\% \) using readout error mitigation.

Errors occurring during the quantum circuit can be mitigated using Richardson extrapolation \([43]\). First, the quantum circuit is run using a rescaled Hamiltonian to amplify the effect of the noise. Second, a Richardson extrapolation is used to extract the result of the quantum circuit at the zero noise limit. In hardware, error mitigation is done by stretching the duration of the gates. For each stretch factor the qubit gates need to be recalibrated \([8]\). Here, we use a simplified error mitigation protocol that circumvents the need to recalibrate the gates but still allows us to increase the accuracy of the quantum hardware \([44]\). Since the single-qubit and CNOT gates have an average randomized benchmarking fidelity of 99.7\% and 97.8\%, respectively, we restrict our error mitigation to the CNOT gates. Furthermore, because the optimized circuit for \( A \{0\}_3 \) contains only 4 CNOT gates, we employ the error mitigation protocol only when evaluating \( QA\{0\}_3 \) which consists of 18 CNOT gates.

We run the circuit for \( QA\{0\}_3 \) three times. In each run we replace the CNOT gates of the original circuit by one, three, and five CNOT gates for a total of 18, 54, and 90 CNOT gates, respectively. Since a pair of perfect CNOT gates simplifies to the identity these extra gates allow us to amplify the error of the CNOT gate without having to stretch the gate duration, thus, avoiding the need to recalibrate the gate parameters. As the number of CNOT gates is increased the probability of measuring \( |1\rangle \) tends towards 0.5 for all initial spot prices, see Fig. 16(b). After applying the Richardson extrapolation we recover the same behavior as the option price obtained from classical simulations, see Fig. 16(c). Our simple error mitigation scheme dramatically increased the accuracy of the calculated option price: it reduced the error, averaged over the initial spot price, from 62\% to 21\%.

VI. CONCLUSION

We have presented a methodology and the quantum circuits to price options and option portfolios on a gate-based quantum computer. We showed how to account for some of the more complex features present in exotic options such as path-dependency with barriers and averages. The results that we show are available in Qiskit Finance \([34]\). Future work may involve calculating the price derivatives \([45]\) with a quantum computer. Pricing options relies on AE. This quantum algorithm allows a quadratic speed-up compared to traditional Monte Carlo simulations but will most likely require a universal fault-tolerant quantum computer \([46]\). However, research to improve the algorithms is ongoing \([47–49]\). Here we have used a new algorithm \([22]\) that retains the AE speed-up but that uses less gates to measure the price of an
option. Furthermore, we employed a simple error mitigation scheme that allowed us to greatly reduce the errors from the noisy quantum hardware. However, larger quantum hardware capable of running deeper quantum circuits with more qubits than the currently available quantum computers is needed to price the typical portfolios seen in the financial industry. Future work could focus on reducing the number of quantum registers in our implementation by performing some of the computation in-place.

VII. ACKNOWLEDGMENTS

The authors want to thank Abhinav Kandala for the very constructive discussions on error mitigation and real quantum hardware experiments.

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Appendix A: Circuit implementation of weighted sum operator

1. Weighted sum of single qubits

In this appendix, we demonstrate an implementation of the weighted sum operator on a quantum circuit. The weighted sum operator $\mathcal{S}$ computes the arithmetic sum of the values of $n$ qubits $|a\rangle_n = |a_1 \ldots a_n\rangle$ weighted by $n$ classically defined non-negative integer weights $\omega = (\omega_1, \omega_2, \ldots, \omega_n)$, and stores the result into another $m$-qubit register $|s\rangle_m = |s_1 \ldots s_m\rangle$ initialized to $|0\rangle_m$. In other words,

$$\mathcal{S} |a\rangle_n |0\rangle_m = |a\rangle_n \sum_{i=1}^{n} \omega_i a_i \rangle_m,$$

(A1)

where

$$m = \left\lfloor \log_2 \left( \sum_{i=0}^{n} \omega_i \right) \right\rfloor + 1.$$

(A2)

The choice of $m$ ensures that the sum register $|s\rangle_m$ is large enough to hold the largest possible weighted sum, i.e. the sum of all weights. Alternatively, we can write the weights in the form of a binary matrix $\Omega = (\Omega_{i,j}) \in \{0,1\}^{n \times n^*}$, where the $i$-th row in $\Omega$ is the binary representation of weight $\omega_i$ and $n^* = \max_{i=1}^{n} n_i$. We use the convention that less significant digits have smaller indices, so $|s_1\rangle$ and $\Omega_{i,1}$ are the least significant
FIG. 17. Three component gates used to construct the weighted sum operator $S$. (a) The carry operator $M$ consisting of one Toffoli gate, which computes the carry from adding $|a_i\rangle$ (or $|c_{j-1}\rangle$) and $|s_j\rangle$ into $|s_{j+1}\rangle$ or $|c_j\rangle$. The bit addition operator $D$ consisting of one CNOT gate, which adds the state qubit $|a_i\rangle$ or the carry qubit from the previous digit $|c_{j-1}\rangle$ to the sum qubit $|s_j\rangle$. (c) The carry reset operator $\tilde{M}$ consisting of two X gates and one Toffoli gate, which resets the carry qubit $|c_j\rangle$ back to $|0\rangle$.

digits of the respective binary numbers. Using this binary matrix representation, $S$ is to add the $i$-th qubit $|a_i\rangle$ of the state register to the $j$-th qubit $|s_j\rangle$ of the sum register if and only if $\Omega_{i,j} = 1$. Depending on the values of the weights, an additional quantum register may be necessary to temporarily store the carries during addition operations. We use $|c_j\rangle$ to denote the ancilla qubit used to store the carry from adding a digit to $|s_j\rangle$. These ancilla qubits are initialized to $|0\rangle$ and will be reset to their initial states at the end of the computation.

Based on the above setup, we build quantum circuits for the weighted sum operator using three elementary gates: X (NOT), CNOT, and the Toffoli gate (CCNOT). These three gates suffice to build any Boolean function [35]. Starting from the first column in $\Omega$, for each column $j$, we find all elements with $\Omega_{i,j} = 1$ and add the corresponding state qubit $|a_i\rangle$ to $|s_j\rangle$. The addition of two qubits involves three operations detailed in Fig. 17: (a) computation of the carry using a Toffoli gate ($M$), (b) computation of the current digit using a CNOT ($D$), (c) reset of the carry computation using two X gates and one Toffoli gate ($\tilde{M}$). When adding $|a_i\rangle$ to the $j$-th qubit of the sum register, the computation starts by applying $M$ and then $D$ to $|a_i\rangle$, $|s_j\rangle$ and $|c_j\rangle$, which adds $|a_i\rangle$ to $|s_j\rangle$ and stores the carry into $|c_{j+1}\rangle$. Then, using the same two operations, it adds the carry $|c_j\rangle$ to the next sum qubit $|s_{j+1}\rangle$ with carry recorded in $|c_{j+1}\rangle$. The process is iterated until all carries are handled. Finally, it resets the carry qubits by applying $\tilde{M}$ in reverse order of the carry computation. We reset the carry qubits in order to reuse them in later computations if necessary.

In general, we need $\max(k-2,0)$ carry qubits to compute the addition of $|a_i\rangle$ on $|s_j\rangle$, where $k \geq 1$ is the smallest integer satisfying

$$k \{ |\rho_{j,j+k-1} \rangle \}^k = 0,$$

where $\rho_{j,j+k-1}$ is the density matrix corresponding to $|s_j\rangle \cdots |s_{j+k-1}\rangle$. In the $k = 1$ case, i.e. $|s_j\rangle = 0$, the computation is reduced to “copying” $|a_i\rangle$ to $|s_j\rangle$ using the bit addition operator $D$, and no carries would be produced. For $k \geq 2$, Eq. (A3) guarantees no carries from $|s_{j+k-1}\rangle$ and beyond. Therefore we can directly compute the sum from $|s_{j+k-2}\rangle$ into $|s_{j+k-1}\rangle$ without worrying about additional carries. This eliminates the need for an ancilla qubit $|c_{j+k-2}\rangle$, and hence the number of carry qubits needed is $k - 2$. To further reduce the number of ancilla qubits, we can use any sum qubit $|s_j\rangle = |0\rangle$ during the computation. In our case, since we are processing $\Omega$ column by column, all sum qubits more significant than $|s_{j+k-1}\rangle$ would be $|0\rangle$. In other words, we have the last $m - (j + k - 1)$ sum qubits usable as carry qubits in the computation described above.

As the weights are known at the time of building the circuit, the possible states that $|s_m\rangle$ can have before each addition of a state qubit $|a_i\rangle$ are also computable. Since we are adding $|a_i\rangle$ to $|s_j\rangle$ starting from the least significant bit, $k$ equals the bit length of the maximum possible sum on $|s_j \cdots s_m\rangle$ after adding $|a_i\rangle$ to $|s_j\rangle$. In other words,

$$k = \log_2 \left| \sum_{u \leq i, v \leq j} \frac{\Omega_{u,v}}{2^{v-u}} \right| + 1. \tag{A4}$$

Therefore, the number of carry operations and additional ancilla qubits required for each addition of $|a_i\rangle$ can be determined. The term in the $|\cdot|\rangle$ in Eq. (A4) is upper-bounded by

$$\sum_{u \leq i, v \leq j} \frac{\Omega_{u,v}}{2^{v-u}} \leq \sum_{j=1}^{m} \frac{n_{\text{max}}}{2^{j-1}} < 2n_{\text{max}} \leq 2n, \tag{A5}$$

where $n_{\text{max}} = \max_{j=1}^{n_{\text{max}}} \sum_{i=1}^{n_\Omega} n_{\Omega_{i,j}}$ is the maximum number of 1’s in a column of $\Omega$. It immediately follows that the number of non-trivial carry operations (i.e. carry operations that requires $M$) required to add $|a_i\rangle$ to $|s_j \cdots s_m\rangle$ is upper-bounded by

$$k - 2 < \log_2 [n_{\text{max}}] \leq \log_2 [n], \tag{A6}$$

and the number of ancilla qubits required for the entire implementation of $S$ is at most the upper bound for $k - 2$, since we may use some sum qubits as carries. In other words, the number of ancilla qubits required for $S$ grows at most logarithmically with the number of state qubits $n$. 
2. Sum of multi-qubit integers

The weighted sum operator $S$ can be used to calculate the sum of $d$ multi-qubit positive integers on a quantum register. To do that we first prepare the input register in the state

$$|a\rangle_n = |a_1^{(1)} \ldots a_{n_i}^{(1)} \ldots a_1^{(d)} \ldots a_{n_i}^{(d)}\rangle, \quad n = \sum_{i=1}^d n_i,$$  \hspace{2cm} (A7)

where $|a_i^{(i)} \ldots a_{n_i}^{(i)}\rangle$, $i \in [1, d]$ is the binary representation of the $i$-th integer to sum with $n_i$ qubits, least significant figure first. Then we set the weights as

$$\omega = (2^0, \ldots, 2^{n_i-1}, \ldots, 2^0, \ldots, 2^{n_d-1}), \quad (A8)$$

or equivalently,

$$\Omega_{n \times n^*} = (I_{n_1 \times n^*}, \ldots, I_{n_d \times n^*})^T,$$  \hspace{2cm} (A9)

where $I_{n_i \times n^*} = (I_{n_i}, 0_{n_i \times (n^*-n_i)})$, $i \in [1, d]$ and $I_{n_i}$ is the $n_i$-dimensional identity matrix. Now if we build a weighted sum operator on the weights in Eq. (A8) and apply it on the input state qubits in Eq. (A7), we would have the sum of the $d$ integers in $|s\rangle_m$.

Fig. 18 shows an example circuit computing the sum of two 3-digit binary numbers represented on a 6-qubit quantum register $|a\rangle_3 |b\rangle_3$, and storing the result into a 4-qubit register $|s\rangle_4$. The circuit is implemented by a weighted sum operator $S$ with weights $\omega = (1, 2, 4, 1, 2, 4)$. The addition of each qubit onto the sum qubits requires one carry gate ($M$) followed by one addition gate ($D$), except for the first bit $|a_1\rangle$ which does not have any carries before its addition. This results in a total of 6 CNOT ($D$) gates and 5 Toffoli ($M$) gates. The 11 gates are grouped in three groups, as is shown in Fig. 18 by dashed boxes. Each group computes the sum of the bits $|a_j\rangle$ and $|b_j\rangle$ into $|s_j\rangle$ and the carry into $|s_{j+1}\rangle$. Note that separate carry qubits are not required, therefore no carry reset operators $M$ are used. In fact, using the above construction for $S$, no extra carry qubits will be required for the addition of any two binary numbers. In general, $S$ requires at most $\lceil \log_2 d \rceil$ ancilla qubits for carrying operations, which directly comes from Eq. (A6).

3. Weighted sum of multi-qubit integers

In addition to summing up $d$ integers equally, a weight $w_i$ may also be added to each integer $a^{(i)}$. In that case, the weight matrix would be

$$\Omega = (w_1 \cdot I_{n_1 \times n^*}, \ldots, w_d \cdot I_{n_d \times n^*})^T.$$  \hspace{2cm} (A10)

In the case where $w_i$ are not integers, we can rescale the values represented on the quantum register by a common factor to make all weights integers. For example, if we are adding two numbers with weights 0.2 and 0.8, we could use integer weights of $w_1 = 1$ and $w_2 = 4$ instead, and reinterpret the resulting sum in postprocessing by dividing it by 5.

Appendix B: Amplitude Estimation without Phase Estimation

To reduce the required number of qubits and the resulting circuit depth, Suzuki et al. have shown that AE can be performed without requiring quantum phase estimation [22]. To this extent, they exploit that

$$Q^k A |0\rangle_n |0\rangle = \cos((2k+1)\theta_n) |\psi_0\rangle_n |0\rangle + \sin((2k+1)\theta_n) |\psi_1\rangle_n |1\rangle,$$

where $a = \sin^2(\theta_n)$, $|\psi_0\rangle$, $|\psi_1\rangle$ are defined in Eq. 2. This circuit is evaluated for different $k = 2^0, \ldots, 2^{m-1}$, for a given $m$, and the probability of a $|1\rangle$ in the last qubit is approximated for each $k$ using $N$ shots. This amounts to $M \times N$ applications of $Q$ in total, where $M = (2^m - 1)$. Combining the estimated probabilities for all $k$ in a single likelihood function and performing a maximum likelihood estimation, they show that the resulting estimation error scales as $O(1/(M \sqrt{N})$, i.e., the algorithm achieves the same quadratic speed-up as AE with phase estimation in terms of $M$.

Note that even though we are only interested in the result of a single qubit, we always measure all three qubits to be able to apply readout error mitigation as discussed in Sec. V.

Appendix C: Optimized Circuit for $QA |0\rangle_3$

In the following, we describe the circuit used for $QA |0\rangle_3$ requiring only 18 CNOT gates. We have that $Q = A S_0 A S_{\psi_0}$, where $S_0 = 1 - 2 |0\rangle \langle 0|$ and $S_{\psi_0} = 1 - 2 |\psi_0\rangle \langle \psi_0|$. $|\psi_0\rangle$ performs reflections on $|0\rangle$ and $|\psi_0\rangle$ on $|0\rangle$, respectively. $S_{\psi_0}$ can be implemented up to a global phase using a single-qubit Z-gate on the last qubit, which is sufficient to differentiate between $|\psi_0\rangle$ and $|\psi_1\rangle$.

$S_0$ is a bit more difficult and we use circuit synthesis for diagonal unitary matrices to achieve an efficient decomposition into gates [50]. This construction lead to 16 CNOT gates for $Q$ and 21 for $QA$, which was still a bit too much to run on real hardware.

To further reduce the CNOT count, we look at the full circuit $QA |0\rangle_3$ and we applied the following optimization steps. The last part in $Q$ is the application of $A$. As mentioned in Sec. V, we can drop the very last CNOT gate and apply it in a classical postprocessing. Furthermore, in $QA |0\rangle_3$, we have $S_{\psi_0}$ between $A$ and $A^1$, i.e. $A^1 S_{\psi_0} A$, where the uniformly controlled $Y$-rotations in $A$ ($A^1$) are right before (after) $S_{\psi_0}$. On the other hand, the $Z$-gate that implements $S_{\psi_0}$ can be decomposed into an $X$-rotation and a $Y$-rotation. The $Y$-rotation can subsequently be absorbed into one of the uniformly controlled $Y$-rotations in $A$ or $A^1$, changing the angles accordingly.

Since the remaining $X$-rotation commutes with the two neighboring CNOT gates from $A$ and $A^1$, we can move the $X$-rotation so that the two CNOT gates cancel each
other. This reduces the CNOT gate count for $Q_{4|0\rangle}$ to 18 and the resulting circuit is reported in Fig. 19.

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FIG. 19. The optimized circuit for $\mathcal{Q} \mathcal{A} \ket{0}_A$ used for the experiments on real quantum hardware. It requires 18 CNOT gates and 33 single qubit gates. The initial spot price is assumed to be equal to 2. The dashed boxes indicate which parts are used for $\mathcal{A}$, $\mathcal{A}^\dagger$, $S_{\psi_0}$, and $S_0$. Note that due to the circuit optimization, some boxes are slightly overlapping.
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