computing

Max-C

QAOA

algorithm
Applying QAOA t

Example - the

How to determi

Relation to Quantu

Adiabatic Algorithm

My result

Found patterns Fractional error

Conclusions and Future

# Quantum Approximate Optimization Algorithm

Performance on Max-Cut using Heuristic Parameter determination

Joost Bus

Delft University of Technology, the Netherlands

23 July 2020

Supervisors

Matthias Möller Carmina G. Almudever

Quantum

Max-Cı

### QAQA

The general algorithm Applying QAOA 1 Max-Cut

Example -Diamond g

the parameters?
Relation to Quantu

My results
Found patterns

Conclusion and Future Research

## Overview

- 1 Quantum computing
- 2 Max-Cut
- 3 QAOA

The general algorithm

Applying QAOA to Max-Cut

Example - the Diamond graph

How to determine the parameters?

Relation to Quantum Adiabatic Algorithm

4 My results

Found patterns Fractional error

**5** Conclusions and Future Research

## Quantum computing

Max-Cu

### OAOA

algorithm
Applying QAOA t

Example - the

Diamond graph

the parameters?

Relation to Qua

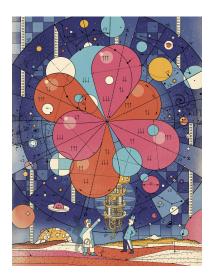
iviy results

Fractional err

Conclusion and Future Research

# Why Quantum Computing?

- Medicine
- Chemistry
- Cryptography
- Optimization



# Quantum computing

Max-Cut

### **QAOA**

algorithm
Applying QAOA

Example - the Diamond grapl

How to determi

Relation to Qu

Adiabatic Algor

My results

Found patterns Fractional erro

Conclusion and Future Research

## Are we there yet?

## The current state of Quantum Computers

- 10 ~ 100 qubits
- Limited connectivity
- Non-negligible error rates
- No error correction

## Quantum computing

Max-Cut

### QAOA

algorithm
Applying QAOA

Example -

How to determi

the parameters

Adiabatic Algori

My results

Found patterns

Fractional erro

and Future Research

## Are we there yet?

## The current state of Quantum Computers

- 10 ~ 100 qubits
- Limited connectivity
- Non-negligible error rates
- No error correction

Do current devices still have useful applications?

# Quantum computing

Max-Cu

### OAOA

algorithm
Applying QAOA

Example - the

How to determi

Relation to Quant

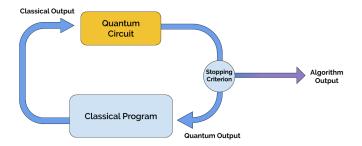
### My resul

Found pattern

Conclusion and Future Research

## Are we there yet?

## Do current devices still have useful applications?



## Quantum computing

Max-Cu

#### $\bigcirc \triangle \bigcirc \triangle$

The general algorithm
Applying QAOA to

Example - the

Diamond graph

Relation to Quantum

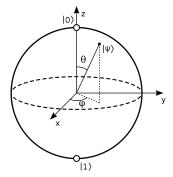
Adiabatic Algorithm

#### My result

Found patterns

Conclusions and Future

## Quantum Computing - The basics



# Quantum computing

Max-Cu

QAOA

algorithm
Applying QAOA

Example - the

How to determ

Relation to Quantu

My result

Found pattern Fractional erro

Conclusion and Future Research

## Quantum Computing - The basics

One quantum bit or qubit can be described as a **superposition**, or (linear) combination of two states with corresponding **amplitudes** 

$$|\psi\rangle = \alpha_1|0\rangle + \alpha_2|1\rangle \tag{1}$$

# Quantum computing

Max-Cu

QAOA

algorithm

Applying QAOA

Example - the Diamond graph

How to determine the parameters?

My reculte

Found pattern

Conclusions and Future Research

## Quantum Computing - The basics

One quantum bit or qubit can be described as a **superposition**, or (linear) combination of two states with corresponding **amplitudes** 

$$|\psi\rangle = \alpha_1|0\rangle + \alpha_2|1\rangle \tag{1}$$

Similarly, for a two qubit system we the system is described with four amplitudes.

$$|\alpha_1|00\rangle + |\alpha_2|01\rangle + |\alpha_3|10\rangle + |\alpha_4|11\rangle$$
 (2)

Quantum computing

Max-Cu

QAOA

algorithm
Applying QAOA

Example - the Diamond graph

the parameters?

My results

Found patterns Fractional erro

and Future Research

## Quantum Computing - The basics

One quantum bit or qubit can be described as a **superposition**, or (linear) combination of two states with corresponding **amplitudes** 

$$|\psi\rangle = \alpha_1|0\rangle + \alpha_2|1\rangle \tag{1}$$

Similarly, for a two qubit system we the system is described with four amplitudes.

$$\alpha_1|00\rangle + \alpha_2|01\rangle + \alpha_3|10\rangle + \alpha_4|11\rangle$$
 (2)

In general, we need  $2^n$  amplitudes to describe an n qubit system and some say the system is in  $2^n$  states "at the same time". Hence the exponential power of the quantum computer.

$$\alpha_1|0\ldots 0\rangle + \cdots + \alpha_{2^n}|1\ldots 1\rangle$$
 (3)

## Quantum computing

Max-Cu

### QAQA

The general algorithm Applying QAOA

Example - the

Diamond graph

Relation to Quanti

Adiabatic Algorithm

Found patterns

Conclusion and Future Research

## Quantum Computing - The basics

**However**, we are not able to measure the amplitudes directly. Upon measurement, the system **collapses** into *one* classical state with probability related to the magnitude of the corresponding amplitude.

## Quantum computing

TTTG/C

### QAOA

algorithm
Applying QAOA

Example - the

Diamond graph

the parameters?

Relation to Quant Adiabatic Algorith

My results
Found patterns

Fractional erro

and Future Research

# Quantum Computing - The basics

### Example with 2 qubits

Given the following system

$$\alpha_1|00\rangle + \alpha_2|01\rangle + \alpha_3|10\rangle + \alpha_4|11\rangle$$
 (4)

we find the following results with their corresponding probabilities

State	Amplitude	Probability
00	$\alpha_1$	$ \alpha_1 ^2$
01	$lpha_2$	$ \alpha_2 ^2$
10	$lpha_{3}$	$ \alpha_3 ^2$
11	$lpha_{ t 4}$	$ \alpha_4 ^2$

## Quantum computing

Max-Cu

QAO/

The general algorithm Applying QAOA

Example - the

Diamond graph

Relation to Quantu

Adiabatic Algorithm

Found patterns

Conclusion and Future Research

## Quantum Computing - The basics

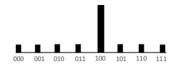
So the amplitudes have a special meaning: the squared magnitude signifies the probability of a particular state. We can change the amplitudes by applying gates, which are descibed by (unitary) matrices.

### Quantum computing

## Quantum Computing - The basics

So the amplitudes have a special meaning: the squared magnitude signifies the probability of a particular state. We can change the amplitudes by applying gates, which are descibed by (unitary) matrices.





Quantum

### Max-Cut

### OAOA

The general algorithm
Applying QAOA to

Example - the

How to determin

Relation to Quantu

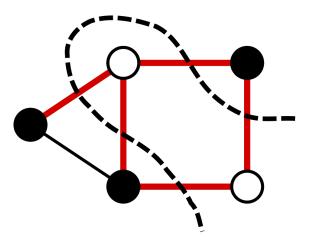
Adiabatic Algorithm

#### My result

Fractional error

Conclusions and Future

## The Max-Cut problem



computing

Max-Cut

QAOA

algorithm
Applying QAOA 1

Example - the

How to determine

Relation to Quantu

Adiabatic Algorithm

My result

Fractional erro

Conclusions
and Future

# We would like to find a **bipartition** that maximizes the following **cost function**

$$C = \sum_{i \in S, j \in \bar{S}} w_{i,j} \tag{5}$$

Quantun

### Max-Cut

QAOA

algorithm
Applying QAOA 1

Example - the

How to determine

Relation to Quantu

Relation to Quantur Adiabatic Algorithm

Found patterns Fractional error

Conclusions and Future Research

# We would like to find a **bipartition** that maximizes the following **cost function**

$$C = \sum_{i \in S, j \in \bar{S}} w_{i,j} \tag{5}$$

Equivalently, we can use a **binary string** to represent the bipartition

$$C = \sum_{\{i,j\}} \frac{w_{i,j}}{2} (1 - z_i z_j) \tag{6}$$

where 
$$\mathbf{z} \in \{-1,1\}^n$$
 and  $z_i = \begin{cases} 1, & \text{if } i \in S \\ -1, & \text{if } i \in \overline{S} \end{cases}$ 

Quantum

Max-Cut

The general algorithm

Applying QAOA

Example - the Diamond grapl

How to determ the parameters

Relation to Quant

Adiabatic Algorithm

Found pattern

Conclusions and Future Research

# The Quantum Approximate Optimization Algorithm

The Quantum Approximate Optimization Algorithm is designed to tackle combinatorial optimization problems. In general, these can be specified with n bits and m clauses. The aim is to satisfy as many clauses as possible

$$C = \sum_{\alpha=1}^{m} C_{\alpha} \tag{7}$$

where  $C_{\alpha} = \begin{cases} 1, & \text{if clause } C_{\alpha} \text{ is satisfied} \\ 0, & \text{if clause } C_{\alpha} \text{ is } \textit{not satisfied} \end{cases}$ 

)uantum

Max-Cut

QAOA

The general algorithm Applying QAOA

Example - the

Diamond graph

Relation to Qua

Adiabatic Algorit

My result

Fractional erro

Conclusion and Future Research

## Schematic of the QAOA circuit

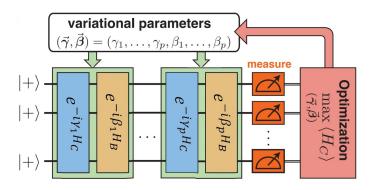


Figure adapted from Zhou et al. Quantum Approximate Optimization Algorithm: Performance, Mechanism, and Implementation on Near-Term Devices (2018)

Quantum

Max-Cut

QAQA

The general algorithm

Max-Cut

Diamond graph

the parameters?

Adiabatic Algorith

My result

Fractional err

Fractional erri

and Future Research

## The Quantum Part

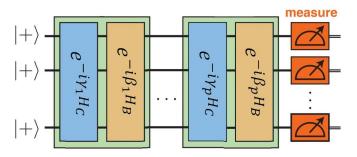


Figure adapted from Zhou et al. Quantum Approximate Optimization Algorithm: Performance, Mechanism, and Implementation on Near-Term Devices (2018)

Quantum computing

Max-Cu

QAOA The general

algorithm Applying QAOA t

Example - th

How to determ

the parameters

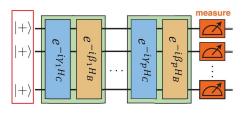
Adiabatic Algor

My results

Found patterns

Fractional erro

and Future Research



We start from  $|+\rangle^{\otimes n}$  which is the **equal superposition** over all  $2^n$  bit strings (or equivalently bipartitions)

$$|+\rangle^{\otimes n} = \frac{1}{\sqrt{2^n}} \sum_{\mathbf{x} \in \{0,1\}^n} |\mathbf{x}\rangle \tag{8}$$

Quantum computing

Max-Cu

QAOA The general

algorithm Applying QAOA 1

Example - tl

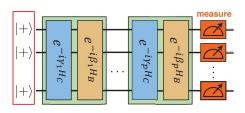
How to determ

Relation to Quantur

Adiabatic Algorithm

Found patterns

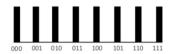
Conclusions and Future



We start from  $|+\rangle^{\otimes n}$  which is the **equal superposition** over all  $2^n$  bit strings (or equivalently bipartitions)

$$|+\rangle^{\otimes n} = \frac{1}{\sqrt{2^n}} \sum_{\mathbf{x} \in \{0,1\}^n} |\mathbf{x}\rangle \tag{8}$$

So the amplitude of every bit string is the same



Quantum

Max-Cu

QAOA The general

algorithm Applying QAOA t

Example - the

How to determi

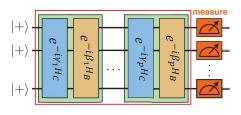
Relation to Qu

Adiabatic Alg

iviy result:

Fractional error

Conclusions and Future Research



Next we alternately apply two gates, the **cost unitary** and the **mixer unitary**, derived from two Hamiltonians.

We repeat this *p* times

Quantum

Max-Cut

### QAOA The general

algorithm Applying QAOA

Example - the

Diamond graph

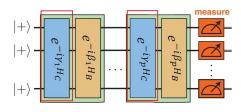
the parameters

Relation to Quant Adiabatic Algorith

My results

Found patterns Fractional erro

Conclusion and Future Research



First of the two being the **cost unitary**. This unitary is derived from the **cost Hamiltonian** that encodes the objective function  $\mathcal{C}$ 

$$H_C \equiv \hat{C} = \begin{bmatrix} C(0,\dots,0) & & & \\ & \ddots & & \\ & & C(1,\dots,1) \end{bmatrix}$$
(9)

Quantum computing

Max-Cut

QAOA The general

algorithm Applying QAOA 1

Example - the

How to determi

the parameter

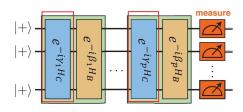
Relation to Qu Adiabatic Algo

Mariana

e .

Fractional error

Conclusions and Future Research



## From the cost Hamiltonian we derive the cost unitary

$$H_C \longrightarrow U(H_C, \gamma)$$
 (10)

with

$$U(H_C, \gamma) = e^{-i\gamma H_C} \tag{11}$$

for some real parameter  $\gamma \in \mathbb{R}$ 

Quantum

Max-Cut

QAOA The general

algorithm Applying QAOA t

Example - the

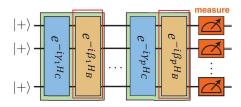
How to determ

Relation to Qua

Adiabatic Algorith

Found patterns

Conclusions and Future Research



# Secondly, the **mixer unitary**, derived from the **mixer Hamiltonian**

$$H_B = \sum_{k=1}^n \sigma_x^{(k)} \tag{12}$$

with  $\sigma_x^{(k)}$  is the Pauli-X gate applied to the kth qubit, which is also called the quantum NOT-gate

$$\sigma_{x} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \tag{13}$$

Quantum

Max-Cut

QAOA The general

algorithm Applying QAOA t

Max-Cut Evample the

Diamond graph

the parameters

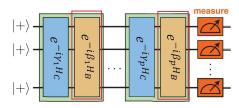
Relation to Qu

NA. . . . . . . . . . . . . . .

Found patterns

Conclusion

and Future Research



Analogous to the cost unitary we derive the **mixer unitary** is derived from the mixer Hamiltonian

$$H_B \longrightarrow U(H_B, \beta)$$
 (14)

the mixer unitary is given by

$$U(H_B, \beta) = e^{-i\beta H_B} \tag{15}$$

for some real parameter  $\beta \in \mathbb{R}$ 

Quantum

Max-Cut

### QAOA The general

algorithm
Applying QAOA to

Max-Cut

How to determ

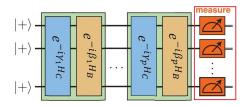
the paramete

Relation to Q Adiabatic Alg

### My result

Found pattern

Conclusions and Future Research



In the end we prepared the parametrized state

$$|\gamma,\beta\rangle = U(H_B,\beta_p)U(H_C,\gamma_p)\dots\underbrace{U(H_B,\beta_1)U(H_C,\gamma_1)}_{\text{one layer}}|+)^{\otimes n}$$

$$p \text{ layers}$$
(16)

after which we measure the outcome.

Quantum computing

Max-Cut

QAOA

The general algorithm Applying QAOA

Example - the

How to determ

the parameters?

Relation to Quantu

Adiabatic Algorith

My result

Found patterns Fractional erro

Conclusions and Future Research

# The goal: maximize the expectation value

Our aim is to prepare a state such that the **expectation value** of the cost Hamiltonian is maximized

$$F_{p}(\gamma,\beta) = \langle \gamma,\beta | H_{C} | \gamma,\beta \rangle \tag{17}$$

for some sequences of parameters

$$\gamma = (\gamma_1, \ldots, \gamma_p)$$

$$\boldsymbol{\beta} = (\beta_1, \ldots, \beta_p)$$

Quantum computing

IVIAX C

QAOA

Applying QAOA to

Max-Cut

Diamond gra

How to determ

Relation to Quanti

Adiabatic Algorithi

My resul

Found pattern Fractional erro

and Future

## Applying QAOA to Max-Cut

We translate the objective function into a Hamiltonian

$$C = \sum_{\{i,j\}} w_{i,j} (1 - z_i z_j)$$
 (18)

$$\downarrow 
H_C = \sum_{\{i,j\}} w_{i,j} \left( I - \sigma_z^{(i)} \sigma_z^{(j)} \right)$$
(19)

computing

NA --- C--

QAOA

Applying QAOA to

Max-Cut

Diamond grap

How to determ the parameters

Relation to Quanti

Adiabatic Algorith

My resul

Found pattern: Fractional erro

Conclusions and Future Research

## Applying QAOA to Max-Cut

We translate the objective function into a Hamiltonian

$$C = \sum_{\{i,j\}} w_{i,j} (1 - z_i z_j)$$
 (18)



$$H_C = \sum_{\{i,j\}} w_{i,j} \left( I - \sigma_z^{(i)} \sigma_z^{(j)} \right) \tag{19}$$

Using the fact  $\sigma_z$  has eigenvalues 1 and -1. Here  $\sigma_z^{(i)}$  denotes the Pauli-Z matrix applied to the ith qubit.

$$\sigma_z = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \tag{20}$$

computing

Max-Cut

### QAOA

### Applying QAOA to

### Max-Cut

Diamond grapl

the parameters

Relation to Quant Adiabatic Algorith

### My result

Found patterns Fractional erro

Conclusion and Future Research

## Applying QAOA to Max-Cut

We can construct the necessary unitaries with local operators

$$U(H_C, \gamma) = e^{-i\gamma H_C} = \prod_{\{i,j\} \in E} e^{-i\gamma w_{i,j}(1 - \sigma_z^{(i)} \sigma_z^{(j)})}$$
(21)

$$U(H_B, \beta) = e^{-i\beta H_B} = \prod_{k \in V} e^{-i\beta \sigma_x^{(k)}}$$
 (22)

Note that the circuit is dependent on the graph G = (V, E)

Now we are set to construct the circuit for Max-Cut!

Quantum

May Cur

OAOA

algorithm
Applying QAOA t

Example - the

### Diamond graph

the parameters?

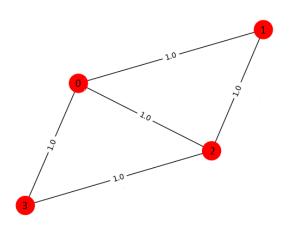
Relation to Quantum Adiabatic Algorithm

Found pattern

Fractional erro

and Future Research

## Example - the Diamond graph



Quantum computing

Mary Cont

### OAOA

algorithm
Applying QAOA

#### Example - the Diamond graph

### How to determi

Relation to Quanti

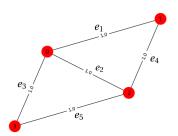
Adiabatic Algorithm

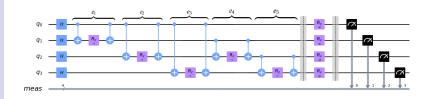
### My result

Found patterns Fractional error

Conclusion and Future

## Example - the circuit





Quantum computing

### Max-Cut

### QAQA

algorithm
Applying QAOA 1

### Example - the

Diamond graph

the parameters?

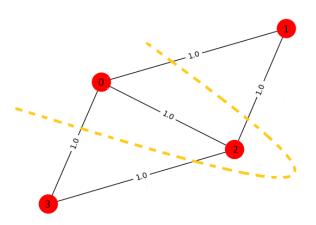
Relation to Quant Adiabatic Algorith

### Mv resul

Found pattern

Conclusions and Future

## Example - the optimal cut



Note that the optimal cut is  $S = \{0, 2\}, \overline{S} = \{1, 3\}$  or in terms of a binary string 0101 or 1010

Quantum computing

### May Cut

### QAOA

algorithm
Applying QAOA 1

#### Example - the Diamond graph

How to determine the parameters?

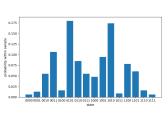
Relation to Quantum Adiabatic Algorithm

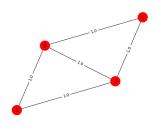
### My result

Found patterns Fractional error

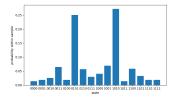
Conclusion and Future

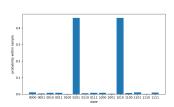
## Example - Maximizing the expectation value





 $p=1, F_1 = 3.24$ 





Quantum computing

# May Cut

# QAOA

algorithm
Applying QAOA 1

#### Example - the Diamond graph

How to determine the parameters?

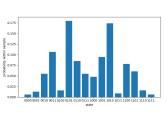
Relation to Quantum Adiabatic Algorithm

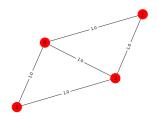
## My resul

Found patterns Fractional erro

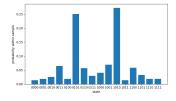
Conclusions and Future

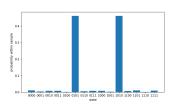
# Example - Maximizing the expectation value





 $p=1, F_1 = 3.24$ 





 $p=2, F_2 = 3.39$ 

 $=3, F_3 = 3.87$ 

Quantum computing

#### . Maria Cont

# QAQA

algorithm
Applying QAOA 1

### Example - the Diamond graph

How to determine the parameters?

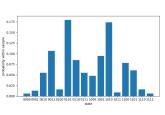
Adiabatic Algorithm

## My result

Found patterns Fractional erro

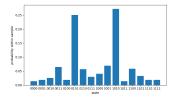
Conclusions and Future

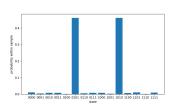
# Example - Maximizing the expectation value



10

 $p=1, F_1 = 3.24$ 





 $p=2, F_2 = 3.39$ 



(uantum

Max-Cut

QAQA

The general algorithm Applying QAOA

Example -

How to determine

the parameters?

Relation to Quanti

Managedia

Found patter Fractional en

Conclusion

# Determining the parameters $\gamma, oldsymbol{eta}$

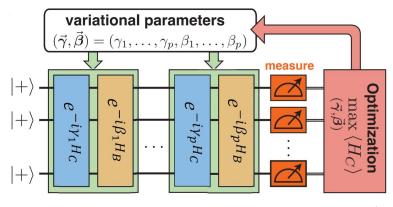


Figure: Schematic of the QAOA circuit using VQE optimization.<sup>1</sup>

<sup>&</sup>lt;sup>1</sup>Figure adapted from Zhou et al. Quantum Approximate Optimization Algorithm: Performance, Mechanism, and Implementation on Near-Term Devices (2018)

Quantum

Max-Cut

QAQA

The general algorithm Applying QAOA

Example - the

Diamond graph

Relation to Quantum

Adiabatic Algorithm

Found natter

Fractional erro

Conclusions and Future

# Relation to Quantum Adiabatic Algorithm

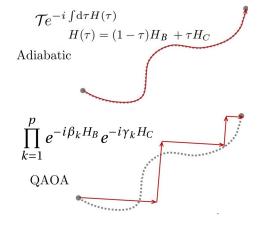


Figure adapted from Verdon et al. A quantum algorithm to train neural networks using low-depth circuits (2017)

)uantum

compacin

## $\bigcirc \land \bigcirc \land$

algorithm
Applying QAOA

Example - the

Diamond graph

the parameters?

Relation to Quantum

Adiabatic Algorithm

My result

Found patter Fractional er

Conclusion: and Future Research

# Relation to Quantum Adiabatic Algorithm

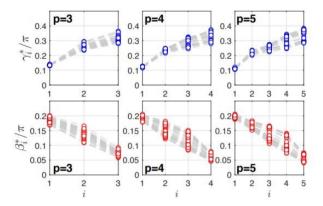


Figure: Optimal parameter patterns for unweighted 3-regular graphs with 16 nodes<sup>2</sup>

<sup>&</sup>lt;sup>2</sup>Zhou et al. Quantum Approximate Optimization Algorithm: Performance, Mechanism, and Implementation on Near-Term Devices (2018)

Quantum computing

Max-Cut

OAOA

algorithm
Applying QAOA

Example - the Diamond gran

How to determi

Relation to Quantum

# Adiabatic Algorithm

My results
Found patterns

Conclusion and Future

# Exploiting the relation to QAA - the INTERP method

Find local optimum



Calculate initial parameters for next p using interpolation



Increment p and repeat until desired depth

Quantum

May Cut

## $\bigcirc \land \bigcirc \land$

algorithm
Applying QAOA t

Example - the

Diamond graph

Relation to Quantum

# Adiabatic Algorithm

Found pattern

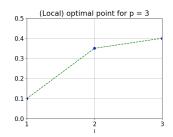
Conclusion:

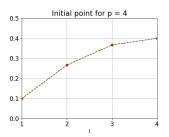
# Exploiting the relation to QAA - the INTERP method

Find local optimum

Calculate initial parameters for next p using interpolation

Calculate initial parameters for desired depth





May Cu

QAOA

algorithm
Applying QAOA 1

Example - the Diamond graph

How to determi

Relation to Quantum

Adiabatic Algorithm

My results
Found patterns
Fractional erro

Conclusions and Future Research

- 1 analysis on INTERP method on different graphs
  - cyclic graphs
  - 3-regular graphs, weighted and unweighted
  - Erdős-Rényi graphs
- ② benchmark against Goemans-Williamson, the best known classical approximation algorithm
- 3 polynomial time

computing

May Cut

 $\bigcirc$ 

algorithm

Example - the

Diamond graph

the parameters?

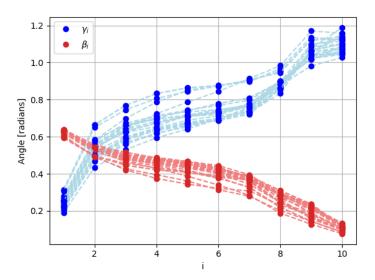
Adiabatic Algorithm

My resul

Found patterns

Conclusions and Future Research

# Found patterns



Quantum

Max-Cu

ΟΔΟΔ

The general algorithm Applying QAOA

Example - the

Diamond graph

Relation to Quant

Adiabatic Algorit

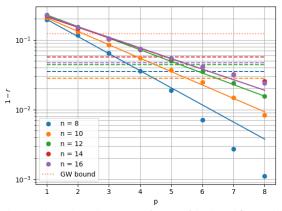
iviy result

Found patterns
Fractional error

Conclusion and Future Research

# Unweighted 3-regular graphs

# Fractional error 1 - r decays exponentially with p



The horizontal lines indicate the average performance of the classical Goemans-Williamson

uantum

May Cut

# QAQA

The general algorithm
Applying QAOA

Example - the

How to determin

Relation to Quan Adiabatic Algorit

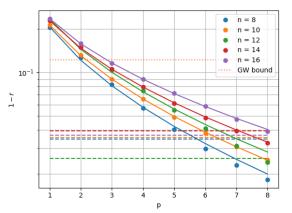
My result

Found patterns Fractional error

Conclusions and Future

# Weighted 3-regular graphs

Fractional error 1-r decays exponentially with  $\sqrt{p}$ 



The horizontal lines indicate the average performance of the classical Goemans-Williamson

Similar relations were found for the Erdős-Rényi graphs

computing

Max-Cu

## QAOA

The general algorithm
Applying QAOA 1

Example - the Diamond graph

How to determine

Relation to Quant Adiabatic Algorith

My result

Found patterns Fractional error

Conclusions and Future Research

# **Conclusions**

- INTERP beats the classical Goemans-Williamson for relatively low p ≈ 7 for small graphs
- The method needs a lot of function evaluations to determine good angles
- However, this number increases polynomially with p and n so it might offer advantages for large graphs

computing

Max-Cut

## QAOA

The general algorithm
Applying QAOA

Example - the Diamond graph

How to determine the parameters?

Relation to Quant Adiabatic Algorith

My result

Fractional erro

Conclusions and Future Research

# Conclusions

- INTERP beats the classical Goemans-Williamson for relatively low p ≈ 7 for small graphs
- The method needs a lot of function evaluations to determine good angles
- However, this number increases polynomially with p and n so it might offer advantages for large graphs

Quantum computing

Max-Cu

## QAQA

The general algorithm Applying QAOA 1

Example - the Diamond graph

the parameters? Relation to Quant

Adiabatic Algorith

Found nattern

Fractional erro

Conclusions and Future Research

# **Conclusions**

- INTERP beats the classical Goemans-Williamson for relatively low p ≈ 7 for small graphs
- The method needs a lot of function evaluations to determine good angles
- However, this number increases polynomially with p and n so it might offer advantages for large graphs

Quantum computing

May Cu

QAQA

algorithm
Applying QAOA to

Max-Cut Example - the

Diamond graph

the parameter

Relation to Quantum Adiabatic Algorithm

My roculty

Count control

Fractional erro

Conclusions and Future Research

# Thank you!

# Questions?

# Time complexity

In Zhou et al. (2018) it was claimed the INTERP method is polynomial in p, and since the quantum circuit has depth 3m + n, we find that the complete INTERP method is polynomial in both n and p, but is this true in practice?

