A Multi-Node Quantum Network with Defects in Diamond

Ph.D. proposal

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November 23, 2018

INTRODUCTION

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> Write a real introduction

CONTENTS

1 RESEARCH GOALS

The goal of my Ph.D. is:

DEMONSTRATION OF QUANTUM APPLICATIONS ON A MULTI-NODE NETWORK

To achieve this goal four experiments are proposed:

1. Generation of genuine multipartite entangled states,

2. Proof of principle demonstration of the Link layer of the future Quantum Internet stack,

3. Teleportation of entanglement,

4. Client-Server secure delegation of quantum computation.

Quantum network applications require entangled states to be performed. Experiments 1 and 3 deal with the generation of the necessary entangled states. Experiments 2 and 4 can be considered actual applications, that use the generated entanglement to perform some useful computation or task.

2 THE NV CENTRE AS A QUANTUM NETWORK NODE

Quantum networks are expected to deliver definitive security for communication, blind quantum computation, improved clock synchronization and more exotic applications such as connecting far apart telescopes [1].

A node of such a network needs to: 1) generate entangled states with other nodes, 2) manipulate quantum states and 3) store quantum states. The Nitrogen-Vacancy (NV) centre in diamond is a promising candidate to act as node of such a network, as it fulfils all the mentioned requirements [2]. Figure 1 summarises the fundamental properties of the NV centre.

Recent work from our group demonstrated the on-demand generation of remote entanglement between two NV centres with rates up to $39\,\text{Hz}$ [6]. Such high rates, three orders of magnitude higher than previous results on the same platform, are a consequence of moving from a two-photon detection protocol, such as the one used in Ref. [7], to a single-photon protocol.

Figure 2 summarises the Single Click Entanglement (SCE) protocol. If only a single photon was detected at the end of the protocol, the state of the two NVs would be $|\psi\rangle = |\uparrow\downarrow\rangle + e^{i\theta}|\downarrow\uparrow\rangle$, a maximally entangled state, where θ is the optical phase difference between the two photons. Since our detectors cannot discriminate between one or more incoming photons, the state of two NVs is actually, in the limit of small probability of detection, $\rho = (1-\alpha)|\psi\rangle\langle\psi| + \alpha|\uparrow\uparrow\rangle\langle\uparrow\uparrow|$.

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3 GENUINE REMOTE MULTIPARTITE ENTANGLEMENT

A two-particle state can either be entangled or separable. When three or more particles are involved in the state, there are more possibilities. The state can be fully separable, where each of the systems can be described independently of the others, partially separable, where some systems are entangled with each other but not all of them are, and genuinely entangled, where none of the systems are separable from each other. It is possible to further categorise genuinely entangled states: if it is possible to transform one state into another via stochastic local operations and classical communication (SLOOC), then we say that the two states are SLOOC-equivalent.

There are then two categories of triparite genuinely entangled states: the ones that are SLOOC-equivalent to the Greenberger-Horne-Zeilinger (GHZ) state, $|GHZ\rangle = (|000\rangle + |111\rangle)/\sqrt{2}$, and the ones that can be transformed into the W state, $|W\rangle = (|001\rangle + |010\rangle + |100\rangle)/\sqrt{3}$. While the W state has the interesting feature of maintaining entanglement even if some of the parties are lost, the GHZ is usually considered more powerful and most quantum network protocols use a GHZ state as a resource .
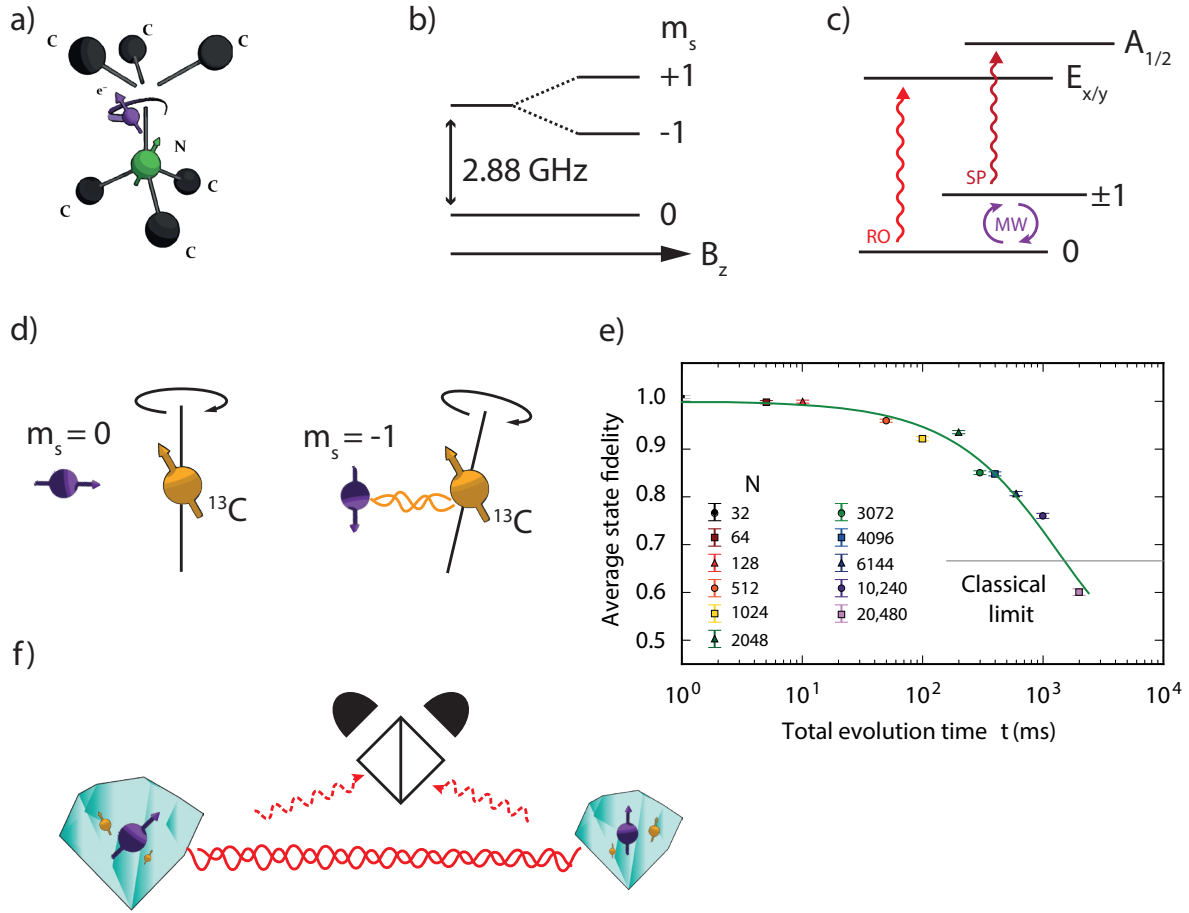
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Figure 1: The NV centre as a quantum network node. a) The NV is an atomic defect in diamond consisting of a neighbouring vacancy and substitutional nitrogen atom. b) After capturing an electron from the environment the centre becomes negatively charged (NV^-) and forms a spin triplet with a zero field splitting of 2.88 GHz. An external magnetic field B_z lifts the $m_s = \pm 1$ degeneracy [3]. c) At cryogenic temperatures (4 K) spin selective optical transitions allow high fidelity single-shot readout (RO) and initialization via spin pumping (SP) [4]. Microwave (MW) pulses allow coherent manipulation of the spin state. d) Non-purified diamond presents a 1.1 % natural abundance of ^{13}C atoms ($S = 1/2$) which couple to the NV centre via a distance-dependent hyperfine coupling. This enables selective addressing of these ^{13}C atoms and universal gates have been shown, making them a good candidate to act as quantum memories [5]. e) Dynamical Decoupling (DD) sequences, tailored to the unique ^{13}C environment of each NV centre, extend coherence times from $T_2^* \approx 5\,\mu s$ to $T_2^{DD} > 1\,s$ [10]. f) The combination of these properties makes it possible to entangle remote NV centres via photon mediated protocols and run complex schemes such as entanglement purification and loop-hole free tests of Bell inequalities [7, 9].
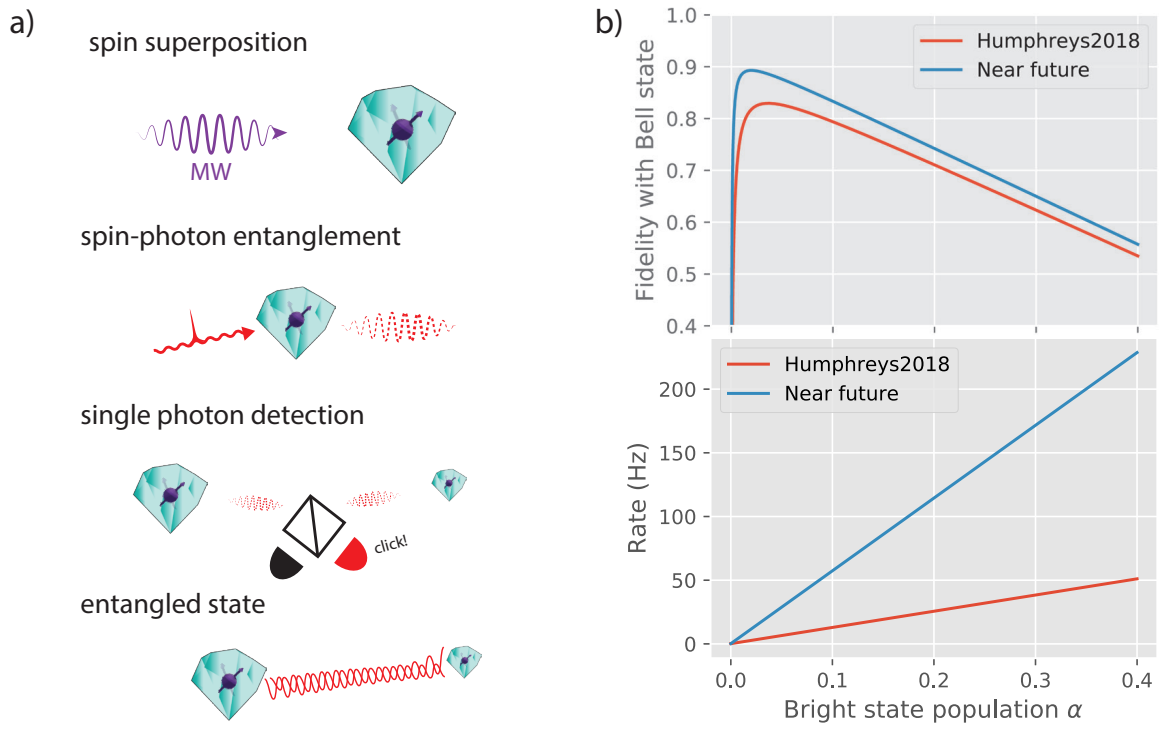
Figure 2: The Single Click Entanglement (SCE) protocol. a) Two remote NVs are put in a superposition state $|\alpha\rangle = \sqrt{\alpha}|\uparrow\rangle + \sqrt{1-\alpha^2}|\downarrow\rangle$ via a MW pulse. A laser pulse resonant with the $|\uparrow\rangle$ state, entangles the presence of a photon with the state of each NV. The two photonic modes interfere on a BS. The detection of a single photon heralds the entanglement between the NVs. b) Performance comparison between Ref. [6] and near-future experiments.
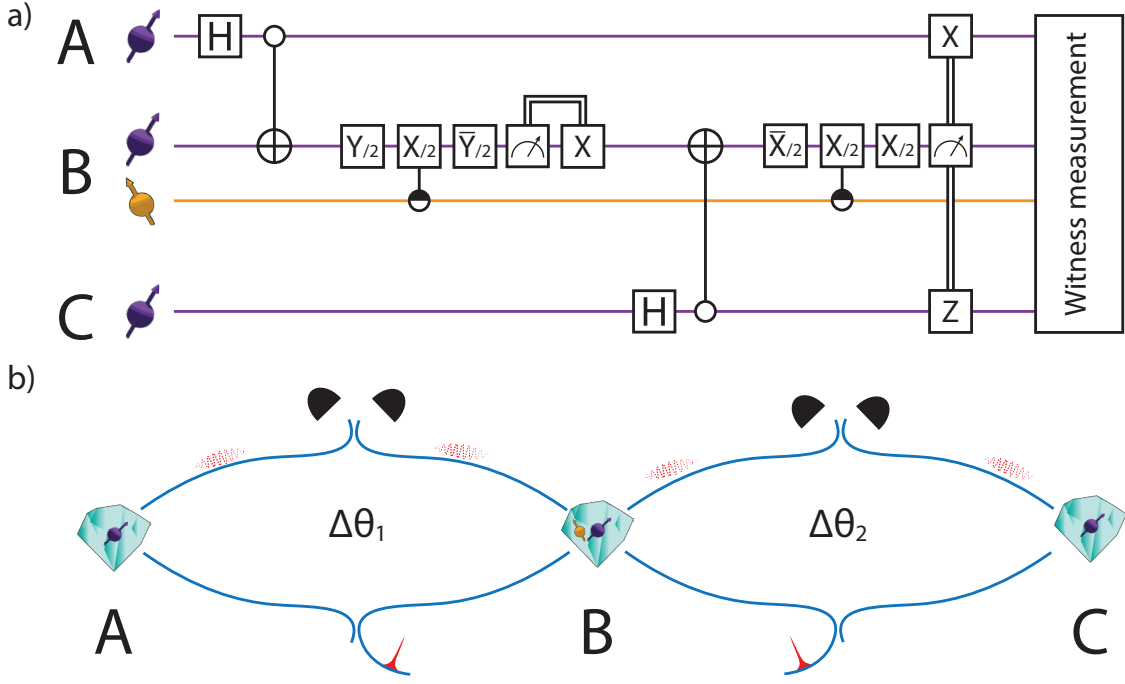
Figure 3: Generation of a remote GHZ state with three NV centres.

	p_{det}	σ_θ	p_{2exc}	$\mathcal{V}$	$N_{1/e}$	t_{ent}	B_z
Ref. [6, 9]	3×10^{-4}	14°	0.04	0.80	275	5.5 µs	400 G
Near-future	1×10^{-3}	20°	0.02	0.90	1000	3.5 µs	2000 G

Table 1: Comparison of experimental parameters for SCE. p_{det} is the probability of detecting a photon in the ZPL. σ_θ is the phase uncertainty of the stabilised interferometer. p_{2exc} is the probability that the NV had already been excited during the pulse if a photon is detected after the pulse. $\mathcal{V}$ is the visibility of the TPQI. $N_{1/e}$ is the lifetime of the quantum memory (see main text). t_{ent} is the duration of one entanglement attempt. B_z is the external magnetic field applied to the NV.

State generation

Generation of remote GHZ states have been demonstrated on the photonic platform [8], and local GHZ states have been generated with NV centres . Moving beyond two-node experiments requires the generation of remote genuine multipartite entanglement. Figure 3 shows the proposed experimental sequence to generate a GHZ state among three remote NV centres.

The experiment requires three experimental setups. Two of them, named LT3 and LT4 (Low-Temperature) are the same setups used in Refs. [6, 9]. In the first year of my Ph.D. I built a new setup, named LT5, which has the same functionalities of the other setups and some upgrades to make it easier to use and more performant. The new setup is in a new laboratory, approximately 20 m from the other two setups, which are 1 m apart.

In Figure 2d there is a comparison between the results in Ref. [6] and estimated entanglement fidelities and rates with near-future experimental parameters (reported in Table 1).

After the first round of SCE is executed, the state of the central node needs to be saved on a memory qubit. This will be done via a SWAP operation similar to the one used in Ref. [9]. A second round of SCE will then take place, which will have a timeout, because of the decoherence of the first entangled state. If a second SCE is successful within the timeout window, a local controlled gate on the central node will entangle the electron and carbon, therefore generating a 4-qubit entangled state. By measuring the

Did we publish it? There is definitely a GHZ folder in the drive

electron of the central node, and feeding back the result to the other nodes it is possible to generate a GHZ state among the three nodes.

It is fundamental, for the success of the protocol, to be able to preserve the first entangled state while the second is being generated. While the state of the electronic spin of node A will be preserved using DD sequences, and can reach up to 1 s of coherence time [10], the nuclear spin on node B will be affected by the attempts to generate entanglement on the electronic spin. The main cause of this decoherence are errors in the MW pulses used in the entanglement generation sequence [11]. These errors limited the *lifetime*[1] $N_{1/e}$ of the quantum memory to ≈ 275 entanglement attempt in past works [9]. As proposed in Ref. [11], an avenue to increase the resilience of the quantum memory to the network activity is to increase the external magnetic field applied to the sample. This will make it possible to run the MW pulses in the entanglement generation closer together, therefore reducing the effect of their errors on the quantum memory. We have updated one of the setups (LT3) to run with a higher magnetic field of 2000 G (instead of 400 G). This should directly improve $N_{1/e}$ to ≈ 1000.

State characterisation

An efficient way to show that a state is entangled is measuring entanglement witnesses [12]. An entanglement witness is quantity that is negative when evaluated on a target state, and positive otherwise. For example the quantity $W_{GHZ} = \mathbb{1}/2 - |GHZ\rangle \langle GHZ|$ is negative on genuine multipartite states (up to a certain noise) and positive for all separable and biseparable states. Measuring a negative value for W_{GHZ} is therefore a witness of a genuine multipartite entangled state. There are two parameters that we can tweak during the experiments: 1) the timeout for the generation of the second entangled state and 2) the bright state population α for the second round of SCE. In Figure 4 the expected value of W_{GHZ} while varying those two parameters. A negative value of the witness (i.e. a fidelity of the generated state $\mathcal{F} > 1/2$) can be obtained with states generated in approximately one minute.

A Monte-Carlo simulation shows that, with near future experimental parameters (Table 1), we would need ≈ 30 hours of (non-consecutive) measurement to show that the witness is negative with a statistical significance of 3σ, and ≈ 70 hours for a 5σ significance.

4 LINK LAYER: A PROOF OF CONCEPT

The Link layer is one of the layers of the network stack, a model that characterizes our current Internet without regard to the technological details of the various implementations, and makes it possible to build complex network applications in a device-agnostic manner. To build a Quantum Internet it is necessary to develop an analogous stack of layers (Figure A1).

The first layer of the stack is the Physical layer. This includes the quantum network nodes (in our case NV centres) and the physical medium used to connect them (optical fibres). It also includes all the implementation specific instrumentation required to run the setups.

The Link layer is the next layer of the stack. In the Internet it takes care of reliably delivering data between adjacent nodes, without regard to the physical medium used by the nodes (cable, optical fibre, radio etc.). In the Quantum Internet stack the Link layer will take care of reliably generating entanglement between two points directly connected, eventually through a quantum repeater.

The proposed experiment is a proof of principle of such a layer without the experimental complications that arise when the two nodes are far apart (thus requiring frequency conversion of the photons and/or a quantum repeater). Our current multi-node experiments are controlled by a combination of time-deterministic micro-controllers and Arbitrary Waveform Generators (AWGs). The code and wave sequences used are highly experiment-specific, and need to be changed manually when a different experiment is required.

The objective of the experiment is to generate entanglement between two nodes using a prototype of the future Link layer. An implementation-agnostic microcontroller with a custom operating system (nodeOS) would control each setup, sending commands to a second microcontroller that knows the specific of the system (in our case an NV centre). A schematic of the experiment is depicted in Figure 5.

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[1] Here *lifetime* does not directly refer to a time, but rather to the number of entanglement attempts necessary to decrease the length of the Bloch vector to $1/e$ of the original value.

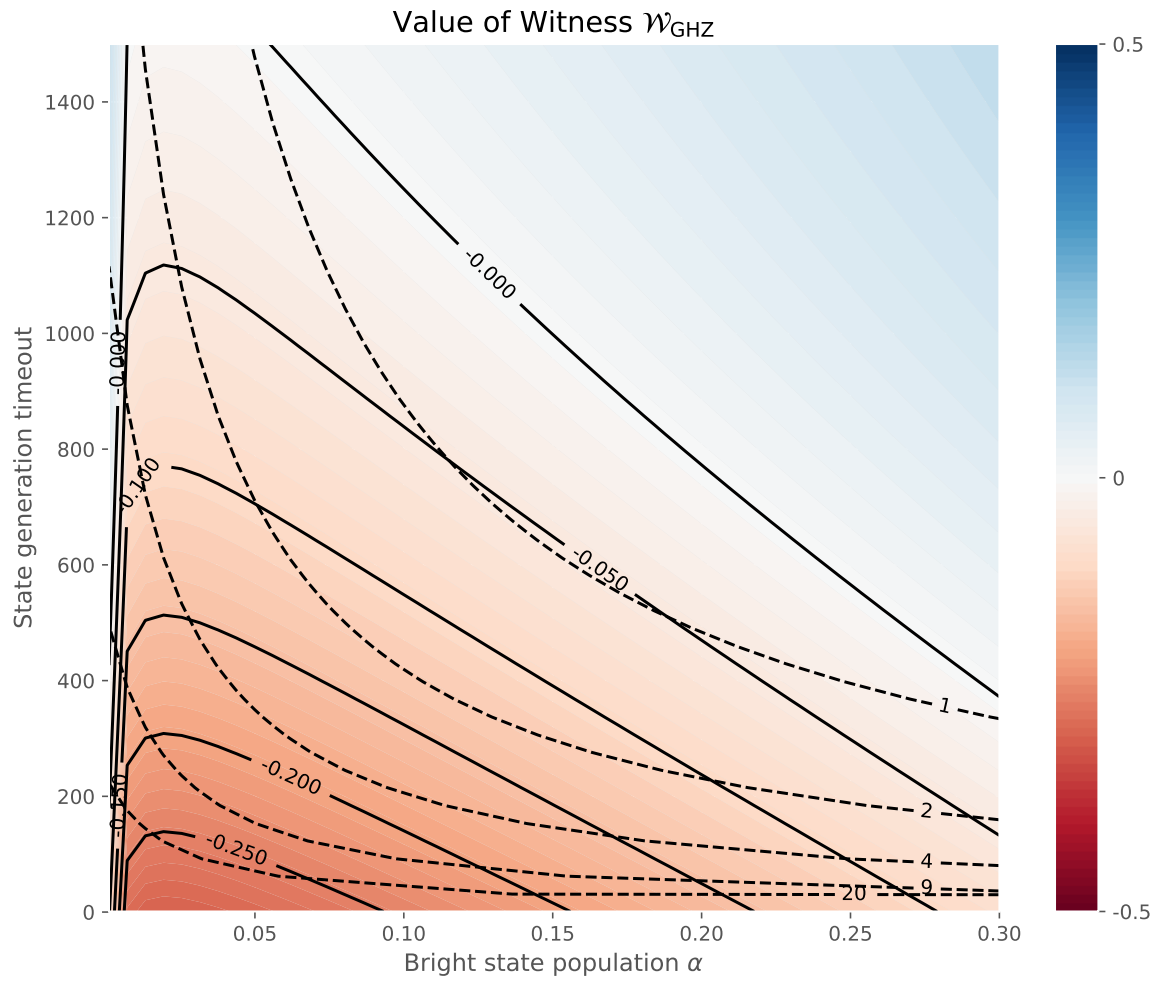## Value of Witness $\mathcal{W}_{\text{GHZ}}$

Figure 4: Simulation of $\mathcal{W}_{\text{GHZ}}$ with near-future experimental parameters. The solid lines on the plot represent curves where the witness value is constant. The dashed lines represent the time (in minutes) that it will take to generate such a state.
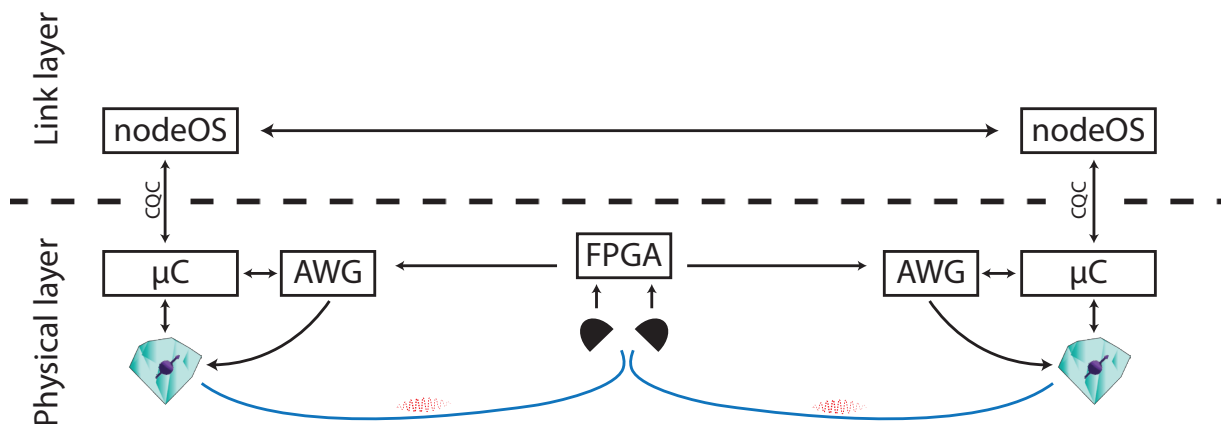
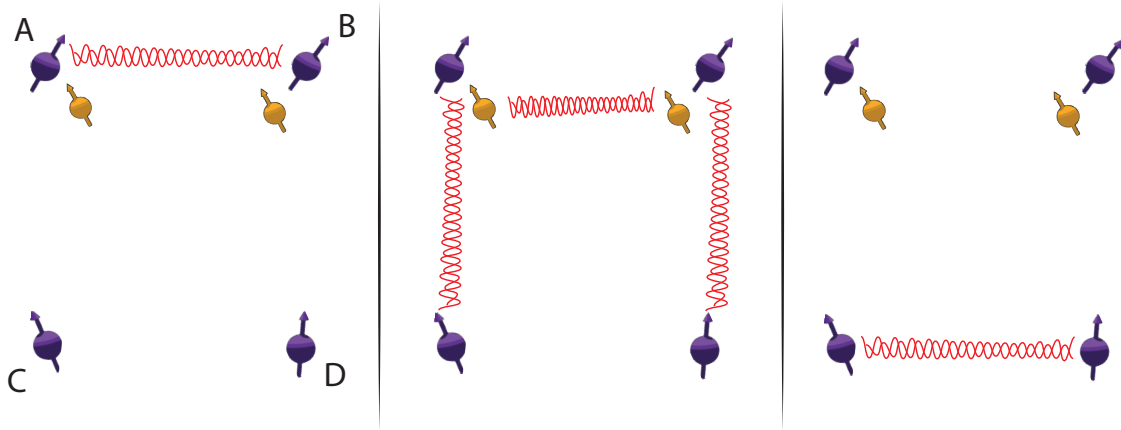Figure 5: Link layer experimental scheme.

Figure 6: Entanglement teleportation experimental scheme. Nodes A and B generate an entangled state with the SCE protocol. The state is swapped to the respective memories. A generates entanglement with C, while B generates entanglement with D. A and B perform a joint state measurement and announce their results. C and D share an entangled state.

The nodeOS controllers will communicate with each other using a direct classical link (an optical fibre, for example), while in the future implementations they would communicate on the Internet. The communication with the Physical link will use a protocol currently in development (**CQC!** (CQC!)) that will later be used on a metropolitan scale in the Demonstrator project. The Link layer will also be able to execute simple quantum operations on the entangled qubits, making it possible to run different small-scale quantum programs without the need to reprogram the experimental setups.

Discuss about current AWG limitations?

Check CQC

5 ENTANGLEMENT TELEPORTATION

Teleportation of quantum states is required by several quantum algorithms . Teleportation of single qubits has been shown on the NV platform by our group [13] and on several other platforms [14–16]. With four network nodes it is possible to deterministically teleport an entangled state to nodes that are not directly connected, allowing them, for example, to run Quantum Key Distribution (QKD). Figure 6 depicts the experimental scheme.

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A fourth NV node will be built to perform this experiment, and two of the four nodes (A and B) will require a ^{13}C quantum memory. The same near-future experimental parameters described in section 3 will also allow this experiment to be performed. In particular, the lifetime $N_{1/e}$ of the quantum memories will play an important role: if the lifetime becomes comparable to the required number of entanglement attempts, the protocol could be executed on-demand. A first possibility is to apply an even higher magnetic field (0.5 T or more), which would decrease the effect of MW errors by making the pulses closer together (see Ref [9]). A drawback of this approach is the need for vector sources that would need to reach up to 20 GHz, and a new cryostat design that could house the needed magnet and deliver such high frequency signals with acceptable attenuation. A second option is to use Radio Frequency (RF) pulses to decouple the memory qubit from the environment, which would only require the additional mixing of RF and MW signals with respect to the current setup [17].

6 CLIENT-SERVER SECURE DELEGATION

One of the key features of quantum networks is Blind Quantum Computation (BQC). A client, without any quantum computation power but the ability to generate single qubit states, interacts with an untrusted quantum server, capable (or not) of universal quantum computation. Quantum mechanics allows for a protocol where the server will execute for the client a computation, without being able

to access the client's information, computation or results. The classical analogue is based on the assumption of the server's (or adversary's) limited computational power (just like RSA encryption).

A proof of principle experiment on the photonic platform was realized in 2012 [18]. The proposed experiment on the NV platform would follow the same experimental scheme, while allowing for an heralded execution.

The client would teleport, one at a time, random quantum states of the form $|\theta\rangle_j = (|0\rangle + e^{i\theta_j}|1\rangle)/\sqrt{2}$, with $\theta_j \in \{0, \pi/4, \ldots, 7\pi/4\}$. The server, upon receiving the qubits, stores them in quantum memories and applies C-Phase gates to consecutive qubits. At this point the client will communicate which measurements to perform (and in which bases). This allows the client to perform universal quantum computation, without sharing private information with the server. The readout bases, and the measurement outcomes, must be combined with the knowledge of the initial states (that only the client has) to obtain information about the computation performed and/or the result.

To perform this experiment on our platform we need to store multiple qubits on the ^{13}C quantum memories while generating more entanglement. As discussed in section 5, an increase in the lifetime on the memories is necessary (by at least an order of magnitude with respect to the current value) to be able to run more than one round of SCE generation. A viable alternative, which is being researched in our group, is the combined use of close-by NV centres. One of the NV centres is used as an optical interface to generate remote entanglement. Once entanglment is established, the state can be swapped to the second NV centre, which has then access to several quantum memories. In this way the memories would not experience the decoherence due to the entanglement generation attempts.

7 PH.D. TIME-LINE

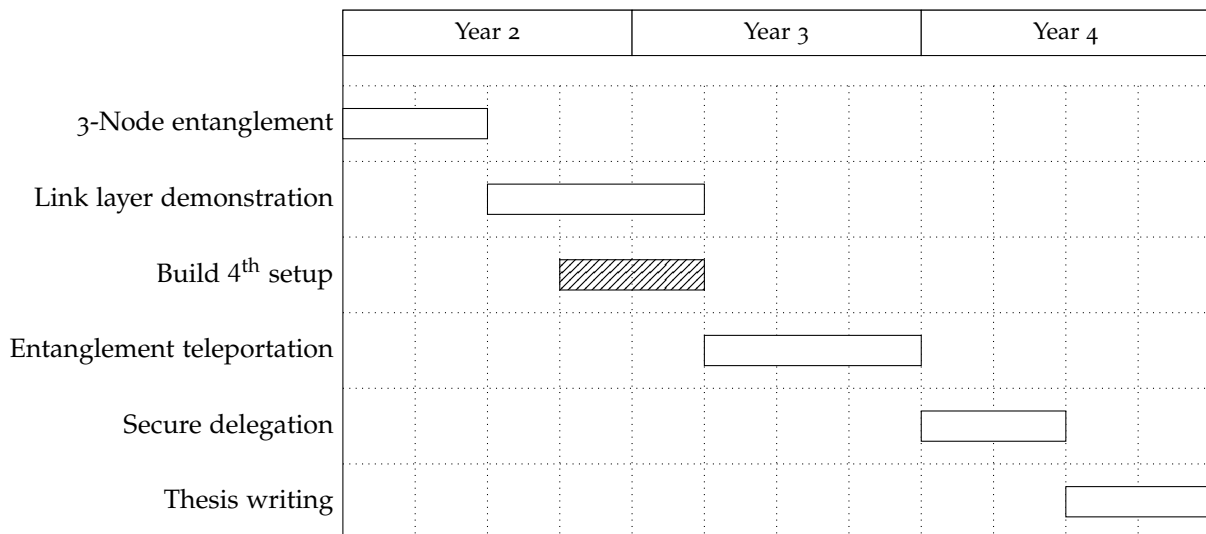The Gantt Chart with the proposed Ph.D time-line is in Figure 7.

Figure 7: Proposed Ph.D. time-line: *3-Node entanglement* is discussed in section 3. *Link layer demonstration* in section 4. *Build 4th setup* will not be a full time activity, but rather support to another Ph.D. student. *Entanglement teleportation* is discussed in section 5, and *Secure delegation* in section 6. The last six months will be used to write the Thesis.

8 GRADUATE SCHOOL PROGRESS

Courses

I attended (or I am currently attending) the following courses:

- Collaboration across disciplines (2 GSC) _____

certificate from Ronald?

- PhD Start-up (2 GSC)

- Conversation skills (2 GSC)

- Casimir Course - Programming (5 GSC)

- Casimir Course - Electronics for Physicists (5 GSC)

- QuTech Academy - Quantum Communication and Cryptography (5 GSC)

Supervision

I have been supervising Hans K. C. Beukers, a MSc student, since February 2018. Hans has been working on setup improvements and techniques that, if successful, will increase the lifetime of our memory qubits. He will graduate in February 2019.

Outreach

As an Early Stage Researcher (ESR) in the Marie Skłodowska-Curie Actions (MSCA) Innovative Training Network (ITN) Spin-NANO, I have to carry out outreach activities regarding my research field to the wider audience. I have currently carried out two outreach activities:

- January 2018, Sheffield, UK. Introduction to quantum- and nano-technologies to local high-school students, as part of an ITN meeting. ⸤ 1 GSC? ⸥

- September 2018, Brussels, BE. Two days stand about quantum technologies at the European Researchers Night, EU Parlamentarium, mainly to children between 5 and 10. ⸤ 2 GSC? ⸥

ACKNOWLEDGEMENTS

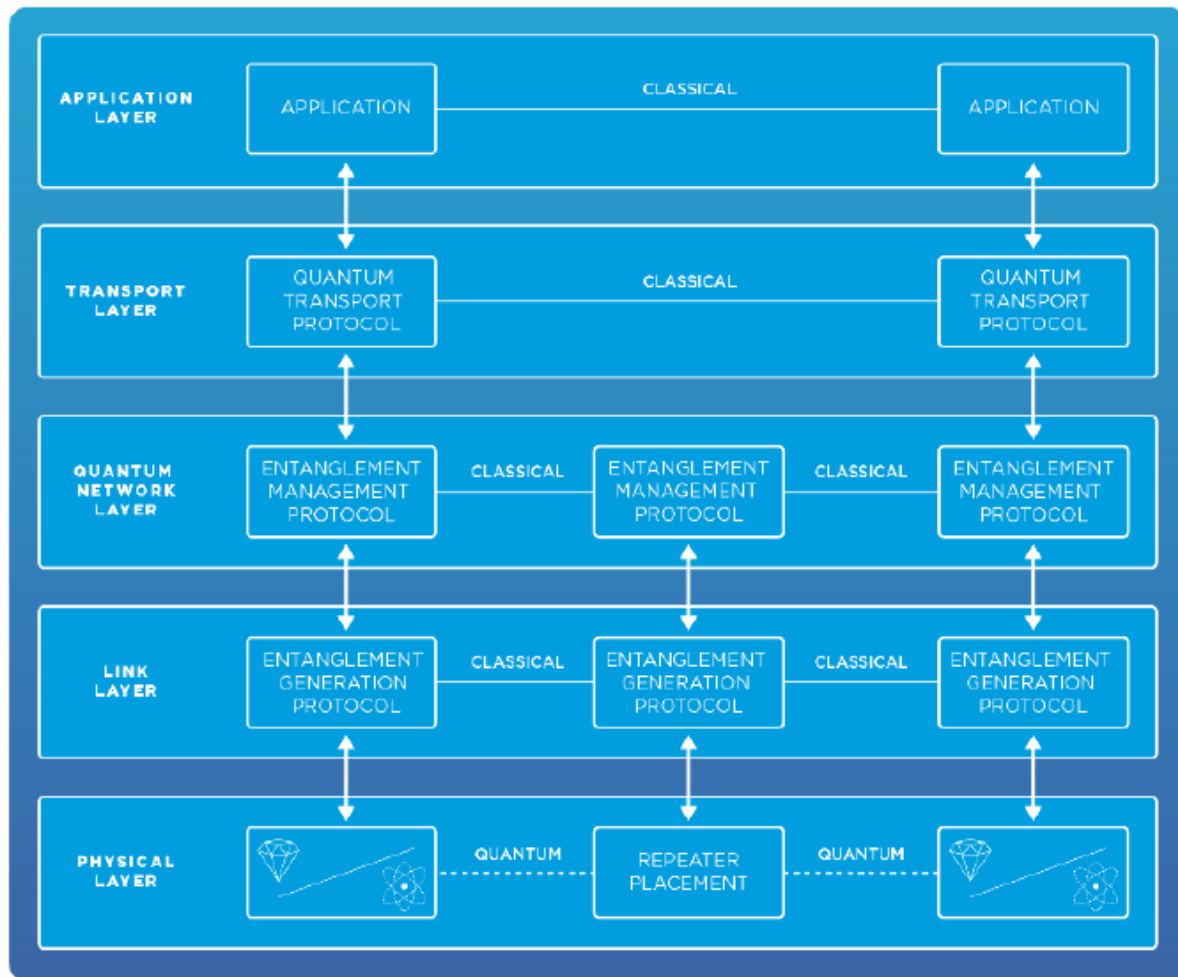I would like to thank everybody. ⸤ actually thank people ⸥

APPENDIX

Figure A1: Proposed Quantum Internet stack

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REFERENCES

[1]   Stephanie Wehner, David Elkouss and Ronald Hanson. 'Quantum internet: A vision for the road ahead'. In: *Science* 362.6412 (Oct. 2018), eaam9288. DOI: 10.1126/science.aam9288.

[2]   David D. Awschalom, Ronald Hanson, Jörg Wrachtrup and Brian B. Zhou. 'Quantum technologies with optically interfaced solid-state spins'. In: *Nature Photonics* 12.9 (Aug. 2018), pp. 516–527. DOI: 10.1038/s41566-018-0232-2.

[3]   Marcus W. Doherty, Neil B. Manson, Paul Delaney, Fedor Jelezko, Jörg Wrachtrup and Lloyd C.L. Hollenberg. 'The nitrogen-vacancy colour centre in diamond'. In: *Physics Reports* 528.1 (July 2013), pp. 1–45. DOI: 10.1016/j.physrep.2013.02.001.

[4]   Lucio Robledo, Lilian Childress, Hannes Bernien, Bas Hensen, Paul F. A. Alkemade and Ronald Hanson. 'High-fidelity projective read-out of a solid-state spin quantum register'. In: *Nature* 477.7366 (Sept. 2011), pp. 574–578. DOI: 10.1038/nature10401.

[5]   T. H. Taminiau, J. Cramer, T. van der Sar, V. V. Dobrovitski and R. Hanson. 'Universal control and error correction in multi-qubit spin registers in diamond'. In: *Nature Nanotechnology* 9.3 (Feb. 2014), pp. 171–176. DOI: 10.1038/nnano.2014.2.

[6]   Peter C. Humphreys, Norbert Kalb, Jaco P. J. Morits, Raymond N. Schouten, Raymond F. L. Vermeulen, Daniel J. Twitchen, Matthew Markham and Ronald Hanson. 'Deterministic delivery

of remote entanglement on a quantum network'. In: *Nature* 558.7709 (June 2018), pp. 268–273. DOI: 10.1038/s41586-018-0200-5.

[7]   B. Hensen et al. 'Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres'. In: *Nature* 526.7575 (Oct. 2015), pp. 682–686. DOI: 10.1038/nature15759.

[8]   Dik Bouwmeester, Jian-Wei Pan, Matthew Daniell, Harald Weinfurter and Anton Zeilinger. 'Observation of Three-Photon Greenberger-Horne-Zeilinger Entanglement'. In: *Physical Review Letters* 82.7 (Feb. 1999), pp. 1345–1349. DOI: 10.1103/physrevlett.82.1345.

[9]   N. Kalb, A. A. Reiserer, P. C. Humphreys, J. J. W. Bakermans, S. J. Kamerling, N. H. Nickerson, S. C. Benjamin, D. J. Twitchen, M. Markham and R. Hanson. 'Entanglement distillation between solid-state quantum network nodes'. In: *Science* 356.6341 (June 2017), pp. 928–932. DOI: 10.1126/science.aan0070.

[10] M. H. Abobeih, J. Cramer, M. A. Bakker, N. Kalb, M. Markham, D. J. Twitchen and T. H. Taminiau. 'One-second coherence for a single electron spin coupled to a multi-qubit nuclear-spin environment'. In: *Nature Communications* 9.1 (June 2018). DOI: 10.1038/s41467-018-04916-z.

[11] N. Kalb, P. C. Humphreys, J. J. Slim and R. Hanson. 'Dephasing mechanisms of diamond-based nuclear-spin memories for quantum networks'. In: *Physical Review A* 97.6 (June 2018). DOI: 10.1103/physreva.97.062330.

[12] Otfried Gühne and Géza Tóth. 'Entanglement detection'. In: *Physics Reports* 474.1-6 (Apr. 2009), pp. 1–75. DOI: 10.1016/j.physrep.2009.02.004.

[13] W. Pfaff et al. 'Unconditional quantum teleportation between distant solid-state quantum bits'. In: *Science* 345.6196 (May 2014), pp. 532–535. DOI: 10.1126/science.1253512.

[14] Shuntaro Takeda, Takahiro Mizuta, Maria Fuwa, Peter van Loock and Akira Furusawa. 'Deterministic quantum teleportation of photonic quantum bits by a hybrid technique'. In: *Nature* 500.7462 (Aug. 2013), pp. 315–318. DOI: 10.1038/nature12366.

[15] Xi-Lin Wang, Xin-Dong Cai, Zu-En Su, Ming-Cheng Chen, Dian Wu, Li Li, Nai-Le Liu, Chao-Yang Lu and Jian-Wei Pan. 'Quantum teleportation of multiple degrees of freedom of a single photon'. In: *Nature* 518.7540 (Feb. 2015), pp. 516–519. DOI: 10.1038/nature14246.

[16] Raju Valivarthi, Marcel.li Grimau Puigibert, Qiang Zhou, Gabriel H. Aguilar, Varun B. Verma, Francesco Marsili, Matthew D. Shaw, Sae Woo Nam, Daniel Oblak and Wolfgang Tittel. 'Quantum teleportation across a metropolitan fibre network'. In: *Nature Photonics* 10.10 (Sept. 2016), pp. 676–680. DOI: 10.1038/nphoton.2016.180.

[17] Conor Bradley et al. In preparation.

[18] S. Barz, E. Kashefi, A. Broadbent, J. F. Fitzsimons, A. Zeilinger and P. Walther. 'Demonstration of Blind Quantum Computing'. In: *Science* 335.6066 (Jan. 2012), pp. 303–308. DOI: 10.1126/science.1214707.

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