TOWARDS A FRAMEWORK FOR THE IMPLEMENTATION OF A SECURE QUANTUM TELEPORTATION INFRASTRUCTURE IN SOUTH AFRICA

by

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DECLARATION

I, Themba James Ngobeni, hereby declare this thesis content constitute my undivided compilation of the research and previously was not submitted in whole nor in part for an academic examination of any qualification. Moreover, it constitute my own thoughts which are not that of Cape Peninsula University of Technology. I believe all consulted material in the build-up of this thesis have been accorded due acknowledgement and referenced accordingly. This study was performed under the supervision and guidance of Mr Amlan Mukherjee and Dr Boniface Kabaso.

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ABSTRACT

The availability of high-speed/high-volume Data Link Layer (Layer 2) transmission networks fuelled by the implementation of mission critical and performance-intensive technologies, such as Cloud and Data Centre services transmitting sensitive data over the wide area network (WAN) has shifted the attention of hackers, eavesdroppers, cyber-criminals and other malicious attackers to the exploitation of these data transmission technologies. It is argued that security on the current classical technologies that store, transmit and manipulate information on the OSI Layer 2 have historically not been adequately addressed when it comes to secure communication and exchange of information. Quantum teleportation (QT) stemming from quantum communication a branch of quantum information science (QIS) has emerged as a technology that promise unconditional security and providing new ways to design and develop frameworks that operate based on the laws of quantum physics. It is argued that it has a potential to address the data transmission security GAP for OSI layer 2 technologies.

This research study aims to propose a framework for the implementation of secure quantum teleportation infrastructures in South Africa. There is currently a lack of generic models and methods to guide the implementation of QT infrastructures that will enable secure transmission of information. A design science research (DSR) was undertaken in order to develop a secure quantum teleportation artefact called (SecureQT-Framework). SecureQT-Framework is a generic model and method that guides the selection and implementation of QT infrastructures motivated by multi-disciplinary domains such as QIS, Quantum Physics, Computer Science as well as information and communication technology (ICT). The DSR process employed a primary DSR cycle with four DSR sub-cycles which involved the awareness and suggestion phase guided by a systematic literature review (SLR), development and evaluation phase guided by Software Defined Network's OpenFlow, Mininet, Mininet-Wifi and computer simulations for QT using SQUANCH framework.

We investigated, examined and collected credible QT techniques and its variant protocols to develop and simulate secure transmission of information over the WAN, We studied their features and challenges. We concluded the study by describing the QT techniques, protocols and implementations that has potential to bridge the security GAP for OSI Layer 2 technologies over the WAN. The results gained were used in the construction of a framework for the implementation of a secure quantum teleportation infrastructure in South Africa. The framework describes the main factors that need to be taken into consideration when implementing quantum teleportation infrastructures.

KEYWORDS: Quantum Teleportation; Layer 2 Data Transmission; Data Security, Quantum Communication, Design Science Research.

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I wish to express my appreciation to**:**

DEDICATION

This study is dedicated to my mother Khanyisa Elizabeth Sibuyi as well as my wife Penelope Makapela together with my children Namely, Thembekile Rivoningo Ngobeni, Lethokwakhe Melokuhle Ngobeni and to my late son Thandolwakhe Ripfumelo Ngobeni who passed-on just after my registration for this study.

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GLOSSARY

Acronyms	Definition
BQCT	Bi-directional Quantum controlled teleportation
BQSDC	bidirectional quantum secure direct communication
BQT	bi-directional quantum teleportation
CBQSDC	Controlled Bidirectional Quantum Secure Direct Communication
CBSQDC	controlled bidirectional secure quantum direct communication
CCTV	Closed-Circuit Television
CHSH	Clauser-Horne-Shimony-Hot
CNOT	Controlled NOT
CPS	Carrier pre-selection
CPUT	Cape Peninsula University of Technology
CQSDC	Controlled Quantum Secure Direct Communication
CSP	Central Security Providers
CV	Continuous variables
DC	Data Centres
DSQC	Direct Secure Quantum Communication
DSR	Design Science Research
DV	discrete variables
EPR	Einstein Podolsky Rossen
FSO	freespace optics
GHZ	Greeberger-Horne-Zeilinger
HDD	Hard Disk Drive
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LAN	Local Area Networks
LEO	Low-Earth Orbit Satellite
LSP	Local Security Providers
MAN	Metropolitan Area network
NMR	nuclear magnetic resonance
OAM	Orbital Angular Momentum
OSI	Open System Interconnection
OSI	Operating System
PDL	polarization-dependent loss
QC	quantum cryptography
QCT	Quantum Controlled Teleportation
QIS	Quantum Information Science
QKD	Quantum Key Distribution
QT	Quantum Teleportation
RAM	Random Access Memory

RO	Research Objective
RQ	Research Question
RSQ	Research Sub-Question
SAL	Serviced Area Licenses
SDC	Super Dense Coding
SDN	Software Defined Networks
SDQC	Secure Direct Quantum Communication
SDQT	Secure Direct Quantum Teleportation
SLR	Systematic Literature Review
SQUANCH	Simulator for QUAntum Networks and Channels
SRQ	Sub-Research Question
USAF	Universal Service and Access Fund
VM	Virtual Machine

CHAPTER ONE
INTRODUCTION AND PROJECT OVERVIEW

The Open System Interconnection (OSI)'s has seven layer reference model, which was published in 1984 by the International Organisation for standardisation (ISO), which outlines how to transfer information between two or more connected computer systems via a network medium. The model is comprised of seven layers, which is regarded as primary conceptual architecture model for inter-computer communication (Margaret Rouse, 2017; da Silva, 2012; Rossi, 2011). The Data Link Layer (Layer 2) of the OSI model has gained more attention since these networks are able to provide performance gains. They also provide benefits such as lower latency, simplicity, flexibility and scalability such that are not possible with Layer 3 Internet protocol networks (Senetas, 2016). This is the main reason why agencies favour Layer 2 transmission technologies for mission crucial and high data-volume WAN operations.

However, in a similar way, the same growth attracted cyber criminals that exploit these information transmission weaknesses through Eavesdropping, Hacking, Sniffing, Scanning and Monitoring of Information. These exploitations have now become critical threats to our modern society as we rely on these technology improvements and capabilities. This current improvement of our conventional technology is referred to as Classical Information Transmission. The Classical Information Transmission is vulnerable to being Sniffed, Copied, Spoofed or Scanned without detection. Quantum Teleportation (QT) promises a new, secure and unconventional way for information exchange within the cyberspace. The breakthrough experiment by (Bennett et al., 1993) and other experts in the field proving a tangible result has paved a way for the society to realize a secure way of exchanging information (Bashar et al., 2009; Humble, 2013; Guzman-silva et al., 2015; Guzman-Silva et al., 2017). These results have created a reduced fear of being Spoofed, Sniffed, Copied or Scanned. This study reports the effect of applying these QT techniques for Data Centres (DC) when exchanging information and thus proposes a framework for their implementation.
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1.1   Research Background

Data Centre (DC) to Data Centre (DC) intercommunication has become a major attraction for exploitation by cyber criminals and other malicious attackers (Jaggi, 2017; Singh et al., 2015; Chelli, 2015). The DC technologies are mission critical implementations that operate on OSI's Layer 2 which is called (Data Link Layer) deploying vital technologies such as BigData, Closed-Circuit Television (CCTV), Multi-Media and Wireless Network Integration to overcome physical environment and bandwidth limitations (Senetas, 2016; Bundy, 2015; da Silva, 2012). This has shifted the attention of hackers, eavesdroppers, cyber-criminals and other malicious attackers to the exploitation of these Layer 2 data transmission technologies as reported by (Senetas, 2016; Singh et al., 2015; Lobel, 2014; Traina et al., 2013). Layer 2

technologies require maximum network performances as well as high-assurance since these networks are able to provide performance gains. They provide amongst other benefits such as simplicity, flexibility, lower latency and scalability not entirely possible with Layer 3 networks (da Silva, 2012; Rossi, 2011; Gallo & Hancock, 2007).

It is argued that network security problems on OSI's Data link layer (Layer 2) have not been adequately addressed according to (Jaggi, 2017; Singh et al., 2015). The "Institute of Electrical and Electronics Engineers (IEEE)" proposed the 802.1AE known as MAC Security (MACsec) standard to secure LAN and MAN, though it is a viable solution for LANs and infrastructure, but security, flexibility and functional requirements for MANs and WANs suffers. If implemented the literature explains that there are challenges as implementation errors and strategically placed backdoors are used to gain access (Jaggi, 2017). It thus further argued that tapping of networks is unpreventable and the consequences of such a breach can be catastrophic whether in the form of data sniffing, technical failure, denial of service, rogue data input or spoofing. The literature further describes that Layer 2 technologies has published vulnerabilities that need urgent redress (Chelli, 2015; Cusack & Lutui, 2015), these authors further classified Layer 2 as the weakest link in the OSI model.

Trustwave Global Data security (2016) reports a finding that 62.5% of data theft takes place while the data is in transit. Cyber security experts in South Africa claim some of the breaches are undisclosed publicly due to the brand reputation, as South Africa's legislation does not compel organizations to disclose (Alfreds, 2016). It further claimed; organizations that are attacked risk not being aware of it. These attacks cause data security in transit to be a major concern for data transmission technologies amongst the cryptographic protocols available to-date (ITU, 2016; Chelli, 2015; Kilor & Soni, 2014). Cryptography is what makes information interchange between different organizations secure in these layers, but a far more secure unconventional communication technology known as Quantum Teleportation (QT) is now emerging as the technology that might enhance or eventually replace classical cryptography in the data transmission technologies.

QT a subfield in "Quantum Information Science" (QIS) is emerging as a new framework to develop Information and Communication Technologies (ICT) that works as per the laws of quantum physics and information theory (Krenn et al., 2017; Zoller et al., 2005; Duplinskiy et al., 2018; Lupo, 2015; Pirandola et al., 2015). Experts points out that by analysing and exploiting specific features of computational models, combining physics and computer science perspectives, QT establishes and presents a framework for

designing protocols that are unconditionally secure and enables the development of ultra-secure communication overcoming the limit of conventional technologies (Ren et al., 2017; Elham, 2015). Travis Humble (Humble, 2007) argues that it provides opportunities to both enhance and radically improve our capabilities for communication and sensing. We further argue that availability of such a framework will help practitioners and academics to integrate such mechanisms and protocols to various existing transmission mediums and allows the creation of secure QT infrastructures to enhance DC to DC intercommunication for backhaul WAN technologies. At the point when a malicious attacker tries to listen in on two entangled particles it will influence the correspondence on the quantum channel, enabling the sender and beneficiary to realize that some individual is attempting to intercept information (Alex Knapp, 2013a). We argue that implementing QT infrastructures will prompt fruitful change of our data economy and adjusting the innovation utilized with the infrastructural needs of the nation.

1.2 Statement of the research problem

Data Centres (DC) intercommunication data networks suffer from exploitation by cyber criminals (Jaggi, 2017; Senetas, 2016). This exploitation may be as a result of the published vulnerabilities and the network security complications on Layer 2 that is said to have not been adequately addressed and in dire need for a redress (Cusack & Lutui, 2015; Chelli, 2015; Pirandola et al., 2015; Singh et al., 2015; Jaggi, 2017; Takeda et al., 2016; Ulrik L Andersen et al., 2014). It is argued that the security gap for DCs intercommunication can be bridged by implementing QT techniques, as it will make it even harder for anyone attempting to exploit the information while in transit. We need to provide empirical evidence that QT techniques have an effect on improving security of information between DCs on the WAN infrastructure in order to adequately propose a framework for their implementation.

1.3 Research aim and objectives

This research aims to investigate the effect of QT on the improvement of DC to DC communication security on the WAN for OSI Layer 2 technologies.

The research objectives are:
1. To design and develop the QT framework for use on Layer 2.
2. To analyse the effect of using QT to securely transmit information.
3. To propose a framework for the implementation of secure QT infrastructures for DC's.

1.4 Research questions and sub-questions

1.4.1 Research questions (RQ)

How can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DCs?

1.4.2 Research sub-questions (RSQ)

1. What QT frameworks and protocols exist to address security challenges for DCs intercommunication over the WAN?
2. How do these recognized solutions in RSQ1 differ? In the approach they address the issues from the perspective of both the utilization of constraints, methodologies or techniques, and what quality of evidence is in support of each solution?
3. What implications do these solutions in RSQ2 have in the design and development of secure QT frameworks for DCs intercommunication over the WAN?

1.5 Purpose and significance of study

Layer 2 Data Centre Intercommunication infrastructures, require a secure way of transmitting information over the Wide Area Networks (WAN) without fear of being hacked, monitored, tapped or scanned. With the advancement of transmission security through the use of the quantum teleportation (QT) mechanism and the opening of the telecommunications sector and universal service and access fund (USAF) Layer 2 transmission technologies are set to improve. For Data Centres the value of the technologies concerned within the QT infrastructure is a vital issue to be taken into thought. The provision of the converged licensing regime, USAF, Under Serviced Area Licenses (USALs) and Carrier pre-selection (CPS) will allow businesses to act as Local Security Providers (LSP) or Central Security Providers (CSP).

This study is inter-disciplinary using quantitative data collection and analysis techniques. It is inter-disciplinary as it draws upon "kernel theories" from reference disciplines such as Quantum Physics, information theory and incorporates them into knowledge from the Information System field. The collection and analysis of quantitative data (from simulations) is under the deductive cognitive process which forms part of a positivist approach.

The design, development and evaluation of an abstract artefact is a key contribution of the study (a framework that can be used in determining which quantum teleportation infrastructure to implement in the particular circumstance that will yield most benefit to Data Centres in South Africa, comprising of models and methods). It must allow the implementation of appropriate quantum information and communication delivery platforms, in order to allow secure transmission of information according to the laws of

quantum physics and based on the data centre's needs. These data centres may range from South African military bases, Department of Defence, Department of Telecommunication and postal services, Health and Finance industry, etc.

The contributions to information system body of knowledge can be described as:

- The application of quantum physics and computer science to deal strictly with the Layer 2 transmission security issues within the existing data centres.
- The use of DSR to design, develop and evaluate a framework for use in implementing quantum teleportation infrastructures.

The information systems contribution can be described as:

- The understanding of how data centres can improve data transmission security by implementing QT infrastructures.
- The framework for implementing QT infrastructures with expected benefits of security when transmitting information.

Moreover, as the basis for information/cyber security, academics and researchers can use or follow the outlined QT models in the framework.

Lastly, the underlying causes of QT deficiencies such as error correction, etc. Nor their specific remedies (e.g. Quantum repeaters, etc.) would not be addressed in this study. Instead building a framework to assist in the implementation of QT infrastructures is the main focus.

1.6 Overview of the methodological approach

The research design study discussed in chapter three, focused on philosophical stand (Design Science Research), following a (abduction, deductive and reflective) research approach, with a strategy (design research).

1.7 Delineation of the research

- This research focuses on the secure transmission of information between two communicating Data Centres utilising Layer 2 transmission technologies over the WAN.
- Technical aspects of the physical quantum teleportation infrastructure are an essential part to the research. QT deficiencies are outside the scope of this research. Instead, we examine what QT's are and their use.
- There are variants of quantum teleportation technologies that allow transmission of information using the different physical QT mechanisms. These technologies are not taken into account since their methods are still in their infancy and not proven in practice.
- The Open Source Simulation Software for Software Defined Networks as well as quantum teleportation tools will be used in the simulation and evaluation of the QT framework.

1.8 Thesis structure

This section provides a structural overview of the research and how it is organised.

Chapter Two: The Review of the Literature

This chapter details various quantum teleportation methods and how they can be used to provide/implement secure transmission of information between Data Centres.

Chapter Three: The Research Design

The research design is detailed in this s chapter and the approach undertaken to realise the research study. Its philosophical standing, research strategy, data collection, data analysis and outputs are discussed.

Chapter Four: Secure QT "Design and Development" Phase

This chapter outlines the "design and development" of the generic SecureQT-framework to guide the implementation of layer 2 data transmission infrastructures. Proposes a SecureQT-framework's Model and Method that will assist in the implementation of secure infrastructures for the transmission of information on the WAN networks for Layer 2 transmission technologies.

Chapter Five: Secure QT Evaluation: Experiment Setup Findings and Interpretation

This chapter details the quantum teleportation simulated experiment for data collection and analysis to test the hypothesis for the study, presents the results of the data collected and analysed during the simulated experiment.

Chapter Six: Conclusion and Recommendation

Concludes the research and outlines possible areas of future research.

1.9   Chapter summary

	THE RESEARCH SCOPE	
1	Introduction	Main research items that were discussed in this chapter have been introduced. The history of OSI Layer 2 has been reviewed to enable and gain an understanding of the research.
2	Research problem background	The origin of the research and background was provided.
3	Statement of the research problem	From (Cusack & Lutui, 2015:81; Chelli, 2015; Pirandola et al, 2015; Singh et al, 2015:503; Jaggi, 2016:86; Takeda et al, 2016; Andersen, 2017) as well as (Senetas, 2016). The research problem was stated. Various role players perceive varying problems associated with cyber security with regards to Layer 2 intercommunication. The origin of these problems and solutions should therefore be investigated.
4	Research aim and objectives	Provided for in section 1.3
5	Research questions and sub-questions	Provided for in section 1.4
6	Purpose and significance of research	Provided for in section 1.5
7	Overview of research design	Provided for in section 1.6
8	Delineation of the research	Provided for in section 1.7
9	Overview of the thesis structure	Provided for in section 1.8

CHAPTER TWO

In chapter one, the research problem has been identified, chapter two details the available Quantum Teleportation Infrastructures and their methods that allow a secure transmission of information over the wide area networks for layer 2 intercommunication technologies.

2.1   Statement of the research problem

The literature on quantum teleportation with relevance to the research study is examined in this chapter; it draws from academic journals, scholarly articles, websites and published literature sources. The study further reviews the main role of quantum teleportation using quantum entanglement to securely transmit information between communicating data centres. A "systematic literature review" (SLR) undertaken to:

- Gather and interpret empirical evidence within the available QT research.
- Compare the solutions with respect to constraints, methods and/or approaches to QT, and identify strengths of the evidence in support of the different solutions found.
- Describe the implications of the findings when creating solutions.

SLR was selected as the basis of this chapter, according to (Okoli, 2017; Okoli & Schabram, 2010) an SLR can be described as "a systematic, explicit, comprehensive and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars and practitioners". SLR ensures that our study follows a defined plan in which the criteria is clearly stated before conducting the review. This allows a transparent and comprehensive search over multiple literature sources that can be reproducible by other researchers. We therefore outlined the search terms and strategies that include search engines, platforms and search dates outlining all exclusions and inclusions.

2.2   Background quantum teleportation defined

QT can be defined as the act by which the quantum state of a system and its correlation can be transferred to another distant system without directly transferring the entity itself (Bashar et al., 2009; Takeda & Furusawa, 2014). As argued by (Humble, 2007; Humble, 2013; Pirandola et al., 2015) this technology can deliver a subtle, un-scan-able kind of information all totally different from standard info, because it is developed in-support of the laws of physics using a concept called "quantum entanglement", where "entangled particles" act as a transformation channel, at a point where an adversary try to listen-in on any two entangled states, it causes the channel to react in a way that allows both parties to realise the presence of an adversary (Alex Knapp, 2013b). These channels for transformation are further exploited by parallel quantum computing and quantum cryptography (Imre, 2014; Hansen et al., 2018). We perceive

quantum cryptography (QC) as the prosperous field where it is possible to apply the concept of quantum teleportation in an efficient and effective way for the data transmission technologies and their related WAN infrastructures.

2.2.1 Quantum teleportation building blocks

Various concepts exist that forms a foundational basis or building blocks of quantum teleportation technologies. These range from quantum bits (qubits), quantum super-position (superposition), quantum parallelism and quantum entanglement.

2.2.1.1   Quantum Bits (qubits)

Qubits represent 0 or 1 state of an atom at any given point, unlike classical states that represent 0 when no current is flowing and 1 when current is flowing on the conducting wires. Qubits as a bi-stable state quantum system can be realised by the Photons, Spin-1/2 particles, Polarization of electrons etc., normally represented in a two-dimensional Hilbert space(Liberty & Keogh, 1996; Barde et al., 2011).

2.2.1.2   Quantum Superposition

The quantum superposition is defined based on a Dirac notation defined as $|0\rangle$ and $|1\rangle$ respectively which is suitable for quantum computation. A superposition according to quantum mechanical laws, the electronic state of an atom is represented by a wave function: Ψ as below:

$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Equation 2.1

This represents complex vectors α and β that satisfy a mathematical condition:

$$|\alpha|^2 + |\beta|^2 = 1$$

Equation 2.2

The above in terms of classical computing can be represented as 00, 01, 10, and 11. However in the quantum world the two bits can represent any of the numbers simultaneously. Increasing the number of qubits will exponentially increase the superposition number, thereby increasing calculating complex numbers quicker (Bashar et al., 2009).
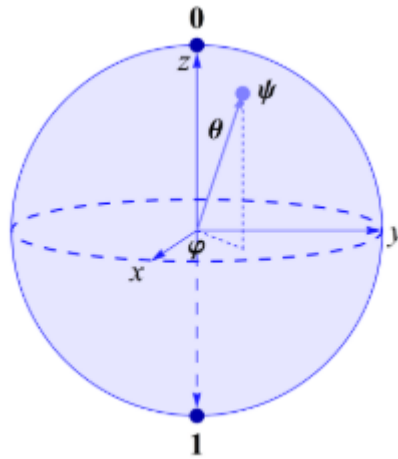
Figure 2.1 Bloch Sphere
Adapted from (Humble & Britt, 2016)

Figure 2.1 above according to (Humble & Britt, 2016) describes "possible values of a single qubit map onto the unit sphere, also known as the Bloch sphere. The upper and lower poles of the sphere correspond to the logical states 0 and 1 respectively. A classical bit can only encode either the logical 0 or 1 state, while a qubit ψ can encode any of the infinite number of superposition states specified by the angles θ and ϕ".

2.2.1.3 Quantum Parallelism

Quantum parallelism has been developed through the principles of quantum superposition, by using parallelism, a computer can factorise large numbers faster than a classical computer (Poulin, 2002).

2.2.1.4 Quantum Entanglement

Entanglement is a term used in quantum theory to describe a process by which the atoms can become *correlated* to predictably interact with each other regardless of how far apart they are. i.e. particles, such as "photons, electrons, or qubits that have interacted with each other retain a type of connection and can be entangled with each other in pairs, in the process known as correlation" by (Wikipedia, 2016). When using superposition and entanglement, information can be transmitted securely from sender to receiver, any attempts by an intruder is detected and the message is disrupted (Mair et al., 2001; Cummins et al., 2002).

2.2.2 Quantum Information processing Degrees of Freedom/Observables

Scientists have argued and presented that quantum information processing development has followed two separate complementary lines of study, in which the main-line followed the implementation of quantum bits (Qubit) protocols, while the other

devoted on the implementation of high-dimensional based Gaussian states such as coherent and squeezed states (Takeda et al., 2015; Furusawa et al., 2017; Ulrik L Andersen et al., 2014). The researchers explained the main reason for separation was the experimental difficulty interconnecting the underlying technologies for the two implementations. The advanced experimental progress has now resulted in the development and the realization of numerous hybrid protocols (Takeda & Furusawa, 2014).

The degrees of freedom/observable describes the quantum states nature of involvement (Ulrik L Andersen et al., 2014; Takeda & Furusawa, 2014). These complementary approaches pursued, each exploit either particle or wave nature of light, each having its own advantages and disadvantages. The discrete nature is referred to as discrete variables (DV) that represent the eigenvalues. The continuum nature of Eigenvalues is referred to as Continuous variables (CV). Due to their pros and cons various research and experiments were conducted to solve the two forms where realm is in digital and the other on analogue information processing, thus a hybrid approach has been presented to bridge the two islands (Ulrik L Andersen et al., 2014; Takeda & Furusawa, 2014).

The realization of DV and CV in the form of hybrid protocols for optical systems resulted in ground breaking experiments and newer proposals. These observables are detailed below.

2.2.2.1 Quantum Teleportation with Discrete Variables (DV)

In quantum information processing a DV information encoding of a single photon can have different degrees of freedom this may include a photon's polarization, time of arrival, spatial mode or electron's spin. The information can be encoded in superposition as equation (1) above. The computational basis of DV in this case is limited to two, and the measurement is described by two components and every eigenvalue is limited to two (Andersen et al., 2014) which is known as qubit, where a two component, "universal two-component projector" can be used to make a measurements which characterizes a state in a two-dimensional Hilbert space Performing quantum communication implementation tasks on a gate of a finite set, employing the implementation of "single qubit and two-qubit" operations (Ulrik L Andersen et al., 2014; Takeda & Furusawa, 2014).

The complete set of gates can be outlined as:

- Single-qubit, Hadamard and Rotation gates $\hat{U}_H, \hat{U}_{PG}$
- Two-qubit controlled NOT gate $\hat{U}_{CNOT}$

From the sets of gates currently, single-qubit gates are realised with linear optics deterministically. However, the two-qubit mode is argued to introduce a very large non-linearity, they can however be realised using probabilistic measurement induced operations even though the overhead is massive (Knill et al., 2001; Kok et al., 2007).

2.2.2.2   Quantum Teleportation with Continuous Variables (CV)

In quantum information processing a CV is an alternative to the finite-level information encoding. CV uses an infinite-level encoding of information known as continuous basis $\{|\chi\rangle\}$. According to Andersen et al. (2014) the continuous basis encoding employs "the amplitude and phase quadrature's of a field mode, the position and momentum of a mechanical oscillator and spin variables of an atomic ensemble". The quantum state on this basis can be arbitrarily expressed as follows:

$$|\Psi\rangle = \int \Psi(x) \, |x\rangle \, dx$$

Equation 2.3

The data is said to have been encoded in the wave function $\Psi(x)$ instead of using discrete numbers for the two-level system (1). These expressions are coined as Gaussian states for the coherent state is the squeezed state and the entangled CV state known as "two-mode squeezed" state. The output measurement of the continuous numbers in this state called eigenvalues can be realised by using a homodyne projector that employs homodyne detector Andersen et al. (2014). By employing a homodyne projector Andersen et al. argued that it is possible to "perform a complete tomography of any quantum state of light".

The complete set of CV gates can be realised and categorised in two types of transformations:

- Gaussian; and
- Non-Gaussian transformation.

The transformation gates include Gaussian and Non-Gaussian: $\{\hat{F}, \ \hat{Z}, \hat{U}_{SUM}, \ \hat{U}_{PG} \}$ namely Single mode Gaussian gates, g Gaussian SUM gate and a two-mode non-Gaussian cubic phase gate. Andersen et al. (2014) and (Furusawa, 1998) argues that CV transformation gates are standard and good enough in a laboratory and sufficient for various large ranges of protocols. However, for universality it is realised by the technical challenging non-Gaussian transformations.

2.2.2.3   Hybrid Quantum Teleportation (DV and CV)

The hybridization of DV and CV devices together with their states exploitation allows the engineering of non-classical, non-Gaussian quantum states. When applied in quantum information processing, tasks allow the fundamental realisation of "quantum

teleportation, quantum error correction (detection), entanglement distillation as well as testing Bell inequalities and performing bell measurement" (Ulrik L Andersen et al., 2014; Takeda & Furusawa, 2014).

In Quantum communication the hybrid elementary protocol is the quantum teleportation (QT) (Bennett et al., 1993). The study by Bennet et al. also describes the reliable transfer of arbitrary quantum states using shared entanglement and classical communication which in-turn forms basis of our research study. The QT process allows the application in the optical domain to, implement any quantum state in principle which includes single-photon-based qubits, it has great potential to being deterministic with linear components.

The Optical hybrid approach with DV is argued to reach fidelities of 100%, but limited due to its probabilistic nature of Bell measurement on linear transformation. Andersen et al., argues that only through the use of "non-Gaussian transformation" or "non-Gaussian ancillary" states can the "teleporter become near- deterministic, allowing an optical hybrid approach to turn an otherwise probabilistic, linear optical qubit teleporter into a fully deterministic device at the expense of the transfer fidelity".

2.2.3 Quantum Teleportation Literature

The experimental breakthrough conducted by (Bennett et al., 1993). followed by other theoretical and practical experimental work of practitioners demonstrated the principle of quantum teleportation in practice and paved a way for a remarkable technical breakthrough to address the question of whether quantum entanglement could be used to implement a teleportation process to transfer information between remotely distant quantum systems (Bashar et al., 2009). The basic teleportation process can be described as follows:
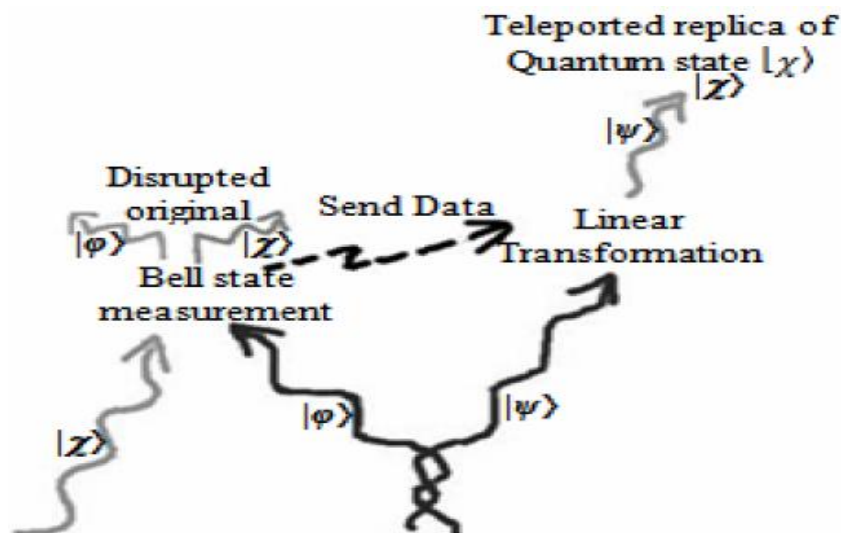
Figure 2.2: Quantum teleportation

The quantum teleportation protocol begins with a quantum state or qubit $|\chi\rangle$, to be teleported from one location to another. This qubit can be written generally, in bra–ket notation, as: $|\chi\rangle = \alpha|0\rangle + \beta|1\rangle$ an equation normally expressed as:

$$|x\rangle = \alpha|0\rangle + \beta|1\rangle$$

Equation 2.4

The quantum teleportation protocol goes as follows as adopted from (Bashar et al, 2009):

1. Prepare a pair of quantum subsystems $|\varphi\rangle$ and $|\psi\rangle$ in an "Einstein–Podolsky–Rosen" (EPR) entangle state. Bell's theorem proved that on a two-qubit quantum symstems there are only four possible entangled states, called the Bell states represented as:

$$|\Psi^-\rangle = \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle)$$

$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle)$$

$$|\Phi^-\rangle = \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle)$$

$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

Equation 2.5

2. We now send $|\varphi\rangle$ to sender A's location and send $|\psi\rangle$ to receiver B's location. The two sub-systems are non-causally correlated via entanglement, though at this point-in-time, they don't have information about $|\chi\rangle$. The two sub-systems now represents an open quantum channel ready to transmit information.

3. Performing the teleportation, now A presents the teleported state $|\chi\rangle$ into communication with the entangled state $|\varphi\rangle$ then a Bell state measurement is performed on the correlated system $|\chi\rangle|\varphi\rangle$.

4. A transmits to B a complete description of the outcome of the measurement utilizing conventional communication channel.

5. The Bell state measurement outcome of A's is $|\Phi+\rangle$ then photon for B is in the state: $|\psi\rangle = -\alpha|1\rangle + \beta|0\rangle$. This means that now B knows the linear set of transformations, and the unitary operation suitable for application to $|\psi\rangle$ in order to obtain the accurate match of the state of $|\chi\rangle$. $|\psi\rangle$ State is now similar to the initial state $|\chi\rangle$ after the linear transformation.

2.2.3.1 Quantum Teleportation Variants

Pirandola et al. (2015) describes teleportation as an important primitive that has been extended in multiple ways. They further define the extensions as real protocols while others in theoretical models have conceptual meaning. Below we list some of such variants:

2.2.3.1.1 Entanglement swapping and Quantum Repeaters

The input for teleportation may itself form part of an entangled state, QT would therefore transfer the entanglement Pirandola et al. (2015). Entanglement swapping variant happens in a case where a third-part performs detection of Bell state while acting as a middle relay. This can be realised by DV and CV as well as a hybrid approach. The approach is said to form the basis of quantum repeaters – where the combination of entanglement swapping and distillation allows for distribution of entanglement over large distances (Briegel et al., 1998; Eisert et al., 2004; Takeda et al., 2015).

2.2.3.1.2 Quantum Teleportation Networks

QT networks is another extension that enables teleportation to be performed between any two parties through the initial sharing of a multipartite entangled state represented by n > 2. Greenberger-Horne-Zeilinger state also allows 3-party assisted networks to be constructed enabling teleportation to be equivalent to "quantum secret sharing", secret sharing allows sender A's quantum information to be recovered by receiver B only if party C assists (Pirandola et al., 2015).

2.2.3.1.3 Quantum gate Teleportation and quantum computing

QT according to (Brassard et al., 1998; Pirandola et al., 2015) can be expressed in terms of primitive "quantum computational operations" allowing its protocol to be extended to "quantum gate teleportation" (Gottesman & Chuang, 1999; Aliferis & Leung, 2004). This method is at the heart of linear-optics and cluster-state "quantum computing" through the use of optical modes implementation (Pirandola et al., 2015).

2.2.3.1.4 Port based Teleportation

The sharing of Bell pairs by party A and B is referred to as Port-Based Teleportation in which party A performs a suitable joint measurement on the system which is to be teleported, then the n qubits, communicates results to party B. an advantage of this technique is that party B does not need to apply a correction at the end of the protocol Pirandola et al. (2015). It is said to also assist as the main tool for to detect violations of Bell inequalities (Buhrman et al., 2016).

2.2.3.2 Physical (Subtrates) Quantum Teleportation Experiments

Various physical quantum teleportation experiments have been realised though others with challenges. Pirandola et al. (2015) on their report details various physical implementations of QT on the laboratory in which they tested a vast amount of variables that lead to a successful implementation of QT. These ranged from Photonic Qubits, Optical Modes, and Atomic ensembles, Trapped Atoms, Solid State and NMR's.

2.3 Systematic Literature Review Quantum Teleportation

2.3.1 Introduction

Systematic literature review (SLR) is a method selected in this study. SLR originates from the medical field that provides a complete, unbiased and exhaustive summary of current literature relevant to a research question, it is a repeatable method that supplies sufficient details that can be easily reproducible by other researchers (Okoli, 2017; Okoli & Schabram, 2010).

2.3.2 Research strategy

The study was conducted using SLR with the aim to gather and interpret empirical evidence from the available research within quantum teleportation, quantum information processing and quantum communication, with respect to our formed research questions, identify gaps and summarize the existing trends in order to provide future research guidelines. This examination has been based on the high-quality reviews and recommendations within software engineering methods described by (Christian et al., 2006). The steps followed while conducting the SLR including planning, conducting and reporting phases are described below.

2.3.2.1 Research questions

A systematic literature review requires that a question should be structured around its method. The aim of the research was to collect and investigate/examine credible quantum teleportation techniques and its relevant protocols, with its physical substrates to allow secure transmission of information over the WAN, study their features, challenges and issues. We wanted to extract special features and methods and the ones recommended by the researchers. The following research questions (RQ) are raised in this paper:

RQ1: How can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DCs?

To finalise the above question, a list of secondary research questions (SRQ's) were formulated as:

- SRQ1: What QT frameworks and protocols exist to address security challenges for DCs Intercommunication over the WAN?
- SRQ2: How do these recognized solutions in SRQ1 differ within the approach they address the issues from the perspective of either the utilization of constraints, methodologies or techniques, and what quality of evidence in support of each solution?
- SRQ3: What implications do these solutions in SQR1 have in the design and development of secure QT frameworks for DCs intercommunication over the WAN?

We executed a protocol search for journal articles and conference proceedings about QT to answer these questions.

2.3.2.2   Planning the review

The SLR was planned to be conducted between February 2018 and December 2018, three researchers were assigned and managed to select the search engines, created the first search string version, and prepared an initial inclusion and exclusion draft criteria to be utilized for papers selection. The information extraction strategy was designed, thereby establishing the evaluation process to ensure quality criteria is met. Few trials were conducted before the final execution of the SLR protocol in order to align components of the researcher's perspectives. We have learned to identify which of the key words to use on different search engines and data sources.

2.3.2.3   Search query

The identification of journal articles and conference proceedings that have investigated quantum teleportation, its protocols and effectiveness into improving security during transmission over the wide area networks was the goal for this search process. The review process for this study adopted the use of the university's search engine that allows us to have access to the needed online scientific databases. We defined a search query string by selecting the most appropriate keywords as guided by the initial trials done in February 2018. The research questions defined were used in the construction of a search string in the databases. By adding synonyms, (singular/plural forms, verbal forms, adjectives), different spellings, broader/narrower terms, and (classification terms used by databases to sort their contents into categories for the question elements), the following search strings were defined:

Title contains: (quantum teleportation OR entanglement OR quantum communication OR quantum information processing) AND

Any field contains: (secure OR physical OR discrete OR continuous OR hybrid OR wireless network OR SDN OR Transmission) AND

Subject contains: (computer science OR information technology OR information theory OR quantum theory OR entanglement OR cryptography OR information processing OR quantum computing)

The search was conducted between 2012 and 2018.

Search limits:

- Research article/journals that are published in a peer reviewed (refereed or scholarly) journal
- Research article/journals written in English, must be open access and available online
- Research article/journals published between (2012 and 2018)
- Publications types are of articles or conference proceedings
- Subject types: Quantum Physics, Computer Science, Information Technology, Information Processing, Information Theory, Quantum Cryptography, Quantum Entanglement

2.3.2.4 Inclusion/Exclusion criteria

Table 2.1: Inclusion/Exclusion Criteria

Inc #	Inclusion	Exc #	exclusion
I1	Title must clearly indicate secure (quantum teleportation, quantum communication, quantum information processing)	E1	Any articles or conference proceedings not indicating security through quantum teleportation, communication, or information processing.
I2	Abstract must contain quantum teleportation approach used e.g. discrete variables, continuous variables or hybrid protocols	E2	Abstract not containing teleportation approaches or protocols
I3	Body must contain quantum teleportation physical substrates e.g.(photonic qubits OR optical modes OR solid state OR trapped atoms OR nuclear magnetic resonance)	E3	Body not containing any physical substrates or their protocols
I4	Articles must contain experiments and findings and must be peer reviewed, available online and open access	E4	Articles without experiments and findings
I5	A comparative controlled study examining the effectiveness of the techniques must be in the article/journal.	E5	Articles without comparative studies or not examining effectiveness of the techniques
I6	Articles must have conclusion/summary/Remarks and references	E6	Articles without conclusion/summary/remarks and references

The criteria for inclusion/exclusion has been outlined in the above table 2.1.

:

Table 2.2 Rationale for Inclusion

Rat#	Rationale
R1	Allows selection of relevant articles meeting inclusion criteria
R2	Assists in identifying relevant articles identifying the techniques or approach used.
R3	Physical substrates help identify the actual application to physically implement QT frameworks
R4	Ensures inclusion of articles that can be fully obtained online and are full papers with open access
R5	Comparative studies on effectiveness assists in identifying techniques that can be used to implement frameworks
R6	Valid articles should follow correct reporting to have conclusion/summary/remarks and references

The rationale for inclusion/exclusion has been outlined in the above table 2.2.

2.3.2.5   Selection of primary studies
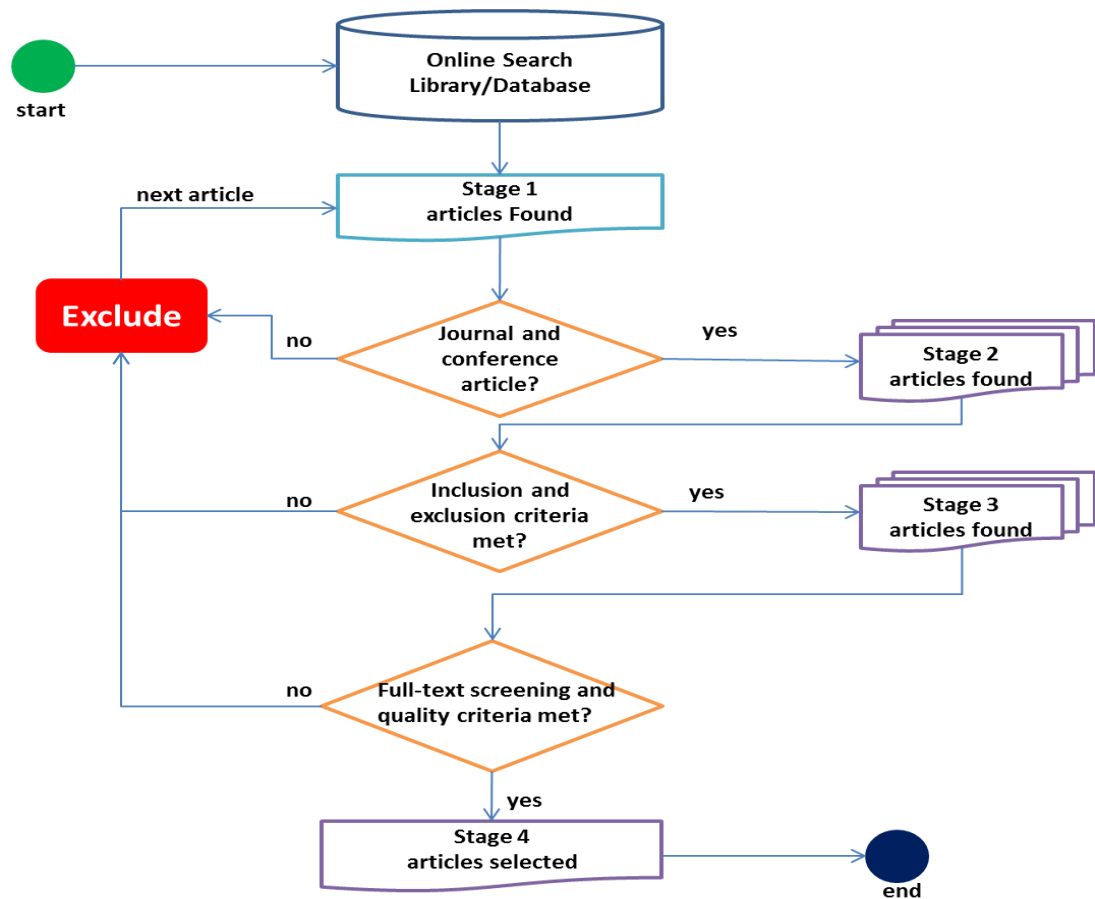
Figure 2.3: primary studies selection process

Figure 2.3 above depicts the process for the primary study selection in the report. The Inclusion/Exclusion criteria as well as quality criteria remained stable throughout the process as indicated in table 2.2 and table 2.4. The set of papers were reviewed based on the criteria as outlined from stage 2 to stage 4. The first stage involved a search in the online databases where the initial identification of articles or journals was conducted. The second stage involved the review of documents based on

inclusion/exclusion criteria, stage 3 involved review based on full-text and quality criteria and stage 4 contained the primary studies identified that met the quality criteria.

2.3.2.6 Data extraction strategy

Table 2.3: Data Extraction Form

Field	Description	Purpose
Engine	Engine Name	to capture the name of the online database engine used
SID	Study Identification	to uniquely identify the study articles
Authors	Author Names	to capture the author's names of the article
Title	Article Title	to capture the title of the research article
Year	Year	to identify the publication year of the article
ERROR-CORRECTION	Error Correction	to indicate if the article addresses error correction within the study
Data Security	Data Security	to indicate if data security during transmission is addressed in the study
Transformation	Transformation	to indicate categories of quantum teleportation transformation used
Quantum Technology	Quantum Technology	to indicate categories of quantum technology used
QT-Approach	Quantum Teleportation Approach	to indicate the quantum teleportation approach followed
Method/Protocol	Method OR Protocol	to indicate the methods or protocols used categorically
Variants/Subtrates/Technique	Physical Substrates, Variants, Techniques	to categorically indicate the substrates, variants or techniques for physical implementation
WAN Infrastructure	Wide Area Networks Infrastructure	to indicate which WAN infrastructure is supported in the article
Quantum Channel	Quantum Channel	to indicate the quantum communication channel used
QT (entangled) States	Quantum States	to indicate the quantum states used
QT Gates	Quantum Teleportation Gates	to indicate the QT gates used
Strength	Strength	to indicate strength of the article
Weaknesses	Weaknesses	to indicate the weakness of the article
Summary	Summary	to summarise the findings on the article
GAP Identified	GAP identified	to identify the GAP in the application

The table above was used as the basis for capturing the data for primary studies in order to understand various elements used when implementing quantum teleportation technologies and analysing their effects on improving data security during transmission over the WAN infrastructure.

Definition of Quality Assessment

The table below outlines the quality assessment criteria, thereby detailing the rationale behind the quality elements to be evaluated against.

Table 2.4: Quality assessment criteria

Quality#	Quality	Rationale
Q1	Article must be peer reviewed and approved for publication, with dates of approval.	Ensures that only peer reviewed articles are selected to ensure its validity.
Q2	Article must have an indication on the physical substrates' of quantum teleportation applied.	Assists in identifying relevant articles identifying the techniques or approach used.
Q3	Article should describe how the data is secured during transmission based on the type of protocol/method being used.	Determines the effectiveness of the technique during transmission
Q4	Article must highlight the security effects of QT techniques on the WAN and WAN infrastructure supported.	Effectiveness assists in identifying techniques that can be used to implement frameworks
Q5	Article should indicate Systematic Literature Review (SLR)	Publication biases are more likely to be avoided with systematic reviews as they provide recommendations that are less biased.

2.3.3 Execution of research protocol

Table 2.5: Online databases

Database Engines	Web Address
Hindawi	www.hindawi.com
SpringerLink	www.springerLink.com
ScienceDirect	www.sciencedirect.com
APS	www.aps.org
ProQuest	www.proquest.com
arXiv	www.arxiv.org
DOAJ	www.doaj.org
IEEE Xplore	www.ieeeXplore.org

Table 2.5 outlines the list of online databases used for collecting Journal/articles for the systematic literature review.

2.3.3.1 SLR Protocol Execution

The research protocol execution was conducted from February 2018 to December 2018. In December 2018 and early January 2019, the research team had the opportunity to review the SLR protocol during a project laboratory workshop at CPUT

campus. Feedback received resulted in the inclusion of the summarization table per database engine and papers selected per year of publication. In order to support the protocol execution, the researchers relied on the approved university ProQuest web tool for the initial sources review and information extraction. The tool provided the capability to use university login and subscription details to obtain all required articles without the need to subscribe or buy articles for full-text evaluation. In addition Mendeley desktop as a data source as well as Microsoft Excel's were used for creation and management of data extraction and quality assessment process.

The initial findings are recorded and detailed as below:

Table 2.6: Initial search execution

Resource	Articles
Articles	1209
Newspaper Articles	379
Conference Proceedings	81
Dissertations	91
Book Chapters	10
Books	8
Reviews	10
Total	**1788**

Table 2.7 outlines the number of articles returned, grouped per resource category. We further broke down the review to include the elements identified as per figure 2.3 and as outlined from Table 2.3 and Table 2.4, the results are listed on Table 2.8 and Table 2.9 below:

Table 2.7: Stages summary

Stage	Description	Articles	Excluded
0th	Online library/database search	1788	-
1st	Journal and article identification met?	216	1572
2nd	Inclusion & exclusion criteria met?	107	109
3rd	Full-text screening	39	68
4th	Quality criteria met?	28	11

Table 2.8: Stages high-level breakdown

Engines	Web Address	2012-2018	1st-stage	2nd-stage	3rd-Stage	4th-Selected
Hindawi	www.hindawi.com	7	2	2	2	2
SpringerLink	www.springerLink.com	740	38	5	4	4
ScienceDirect	www.sciencedirect.com	231	8	1	0	0
APS	www.aps.org	11	3	1	1	1
ProQuest	www.proquest.com	343	5	3	3	0

arXiv	www.arxiv.org	349	147	85	25	17
DOAJ	www.doaj.org	45	10	7	4	4
IEEE Xplore	www.ieeeXplore.org	62	3	3	0	0
	Total	1788	216	107	39	28
	Exclude Total	-	1572	109	68	11

Table 2.10 outlines the primary studies selected that met the quality evaluation criteria as well as passing the inclusion/exclusion criteria. The table has broken down the results per database and per year of publication and finally listing the totals.

Table 2.9: Detailed primary study selection per database

Engines	Web Address	2012	2013	2014	2015	2016	2017	2018	**Total**
Hindawi	www.hindawi.com	0	0	1	0	0	0	1	2
Springer	www.springerLink.com	0	0	0	0	1	1	2	4
ScienceDirect	www.sciencedirect.com	0	0	0	0	0	0	0	0
APS	www.aps.org	0	0	0	0	0	1	0	1
ProQuest	www.proquest.com	0	0	0	0	0	0	0	0
arXiv	www.arxiv.org	1	2	3	2	2	3	4	17
DOAJ	www.doaj.org	0	0	0	2	0	1	1	4
IEEE Xplore	www.ieeeXplore.org	0	0	0	0	0	0	0	0
	Total	1	2	4	4	3	6	8	28

The total of two articles were from Hindawi, four articles from SpringerLink, one article from APS, seventeen from arXiv, four other articles from DOAJ were selected, we however had no articles that passed all required criteria from ScienceDirect, ProQuest as a database not search engine and lastly IEEE Xplore.

The primary study selection has been detailed in section 2.3.3.2 below.

2.3.3.2   Primary Study Selection

Table 2.10: Primary studies selection

SID	Authors	Title	Year
S1	Xiang, Z. *et al.*	Intracity quantum communication via thermal microwave networks	2017
S2	Ma, X. et al.	Quantum teleportation using active feed-forward between two Canary Islands	2012
S3	Yin, J. et al.	Quantum teleportation and entanglement distribution over 100-kilometre free-space channels	2013
S4	Shukla, C. and Pathak, A.	Direct quantum communication without actual transmission of the message qubits	2013
S5	Humble, T. S. and Sadlier, R. J.	Software-defined quantum communication systems	2014
S6	Kaiser, F. et al.	Towards continuous-wave regime teleportation for light matter quantum relay stations	2014
S7	Takeda, S. and Furusawa, A.	Optical hybrid quantum information processing	2014
S8	Takesue, H. et al.	Quantum teleportation over 100 km of fiber using highly-efficient superconducting nanowire single photon detectors	2015
S9	Pirandola, S. et al.	Advances in quantum teleportation	2015
S10	Hassanpour, S. and Houshmand, M.	Bidirectional quantum teleportation via entanglement swapping	2015
S11	Fedortchenko, S.	A quantum teleportation experiment for undergraduate students	2016
S12	Kiktenko, E. O., Popov, A. A. and Fedorov, A. K.	Bidirectional imperfect quantum teleportation with a single Bell state	2016
S13	Gonz, M. D.	Quantum teleportation and information splitting via four-qubit cluster state and a Bell state	2017
S14	Vinay, S. E. and Kok, P.	Practical repeaters for ultra-long distance quantum communication	2017
S15	Hager, M. G., Kirby, B. T. and Brodsky, M.	Modelling quantum teleportation with quantum tools in Python (QuTiP)	2017
S16	Cozzolino, D. et al.	Fibre based high-dimensional quantum communication with twisted photons	2018
S17	Li, C. et al.	Secure quantum communication in the presence of phase- and polarization-dependent loss	2018
S18	Hosseinidehaj, N. and Malaney, R.	Satellite-based continuous-variable quantum communications : state-of-the-art and predictive Outlook	2018
S19	Li, J. et al.	Quantum Secure Direct Communication Based on Dense Coding and Detecting Eavesdropping with Four-Particle Genuine Entangled State.	2015
S20	Lupo, C.	Quantum Data Locking for Secure Communication against an Eavesdropper with Time-Limited Storage.	2015
S21	Ing, L. J. I. et al.	Towards quantum communications in free-space seawater.	2017
S22	Zhang, H. et al.	A Quantum Cryptography Communication Network Based on Software Defined Network.	2018

SID	Authors	Title	Year
S23	Patwardhan, S., Roy, S. and Panigrahi, P. K. (2016)	Efficient Controlled Quantum Secure Direct Communication Protocols.	2016
S24	Rigolin, F. S. L. G. (2017)	Teleportation-based on continuous variable quantum cryptography, Quantum Information Processing.	2017
S25	Duplinskiy, A. V et al. (2018)	Quantam Secured Data Transmission in Urban Fibre-Optics Communication Lines	2018
S26	Kerstel, E. et al. (2018)	Nanobob : a cubeSat mission concept for quantum communication experiments in an uplink configuration	2018
S27	Chou, Y. et al.	Controlled bidirectional quantum secure direct Communication	2014
S28	Shi, L. et al.	Quantum controlled teleportation of arbitrary two-qubit state via entangled states	2018

The categorization of the elements based on the selected primary studies as listed above is depicted below on Figure 2.4:

The number [1] indicates the occurrence of the study under that specific category or subcategory in question. This is in turn used to grade the overall occurrences of the studies within each category/subcategories in order to identify & evaluate the relevant studies which may be of high-value within the scope of this research.

Figure 2.4: Evaluation criteria quantum teleportation

The narration of the table is detailed under results and discussion.

2.3.4   Results

The summary results based on Figure 2.4 above have been arranged into a table in order to group the studies on the level of technology, techniques, protocols and application. The table below provides such a grouping and summarization on the studies.

Table 2.11: Finding summarization

Category	Sub-Category	SID's	Total
ERROR-CORRECTION		S1,S7,S9,S10,S13,S14,S16,S17,S19,S20,S23,S24,S25,S26,S27	15
Data Security	Confidentiality, Integrity, Availability, Non-repudiation	S4,S7,S10,S13,S14,S16,S17,S19,S20,S22,S23,S24,S25,S26,S27	15
Transformation	Single-Qubit Operation	S2,S6,S7,S8,S9,S10, S11,S12,S13,S15,S17,S18,S19,S21,S23,S26,S27	17
	Two-Qubit Operation	S9,S11,S24,S28	4
	Orbital Angular Momentum (OAM)		0
	Unitary	S10,S12,S13,S15	4
	Fourier	S7	1
	Multi-Qubit Gates & Networks	S14,S28	2
Quantum Technology	Photonic Qubits	S5,S6,S7,S8,S9,S11,S14,S15,S18,S20,S21,S22,S25,S26,S28	15
	NMR	S9,S14	2
	Optical Modes	S2,S7,S8,S9,S11,S14,S15,S17,S18,S24	10
	Atomic Ensembles	S9	1
	Trapped Atoms	S9	1
	Solid State	S9,S11,S14,S15,S17,S20	6
QT-Approach	Qubit / Discrete Variables (DV)	S6,S7,S8,S9,S11,S14,S15,S17,S18,S24,S26	11
	Continuous Variables (CV)	S1,S2,S3,S6,S7,S8,S9,S14,S18,S24,S26	11
	Hybrid	S6,S7,S9,S25	4
Method/Protocol	SDQT		0
	DSQC	S4,S19	2
	Dense Coding	S5,S19	2

Category	Sub-Category	SID's	Total
	SDQC	S10	1
	CQSDC	S23	1
	CBQSDC	S27	1
	QCT	S7,S8,S9,S11,S15,S28	6
	BQCT	S10	1
	BQT	S10	1
	QKD	S14,S16,S17,S18,S20,S22,S24,S25,S26	9
	Non-deterministic	S9	1
	Deterministic	S1,S2,S7,S8,S9,S11,S15,S17,S18,S24,S25	11
	Probabilistic	S3,S5,S7,S9,S13,S15	6
Variants/Substrates/technique	Polarization	S3,S5,S6,S7,S8,S9,S16,S17,S18,S21,S25,S26	12
	Single-rail qubits	S9,S15,S18	3
	Dual-rails in free-space	S9	1
	Time-bin	S1,S7,S8,S9,S20	5
	Dual-rails on chip	S9	1
	Spin-orbital qubits	S9,S14,S18	3
	NMR	S9,S14	2
	CV light-to-matter	S6,S9,S14,S18	4
	CV matter-to-matter	S9	1
	DV light-to-matter	S9,S18	2
	DV matter-to-matter	S9	1
	Trapped ions	S9	1
	Trapped ions & photonic carrier	S9,S14	2
	Neutral atoms in an optical cavity	S9	1
	Frequency qubit to quantum dot	S9	1
	Polarisation qubit to rare-earth crystal	S3,S7,S9,S16,S17,S26	6
	Superconducting qubits on chip	S1,S6,S8,S9,S11,S14,S15,S17,S18	9
	Nitrogen-vacancy centres in diamonds	S9	1
WAN Infrastructure	Satellite	S2,S9,S18,S26,S28	5
	Fibre Optics	S2,S6,S7,S8,S9,S15,S16,S17,S25,S28	10
	SDN/ Controller	S5,S10,S22,S23,S27,S28	6
	FreeSpace Optics	S2,S3,S7,S8,S9,S14,S15,S16,S18,S28	10
	Microwave	S1,S9,S14	3

Category	Sub-Category	SID's	Total
Quantum Channel	Thermal Channel (TC)	S1,S9	2
	Classical Channel (CC)	S2,S3,S5,S7,S9,S14,S15,S16,S18,S25,S27,S28	12
	Quantum Channel (QC)	S2,S3,S5,S7,S9,S13,S14,S15,S16,S18,S20,S21,S25,S26,S27,S28	16
	Entanglement *	S2,S3,S6,S7,S9,S11,S15,S16,S19,S23,S26,S28	12
	Sea water	S21	1
	Air-core fiber	S16	1
	Bosonic	S1,S9	2
	LOCC	S9,S12,S15,S27	4
	Unidirectional	S1,S23	2
	EPR	S2,S3,S7,S9,S10,S11,S14,S15,S18,S19,S27	11
QT (entangled) States	BELL	S2,S3,S4,S7,S8,S9,S10,S11,S12,S13,S14,S15,S18,S19,S21,S23,S26,S27,S28	19
	Greeberger-Horne-Zeilinger(GHZ)	S4,S9,S10,S11,S12,S27,S28	7
	GHZ-like	S4,S10	2
	Clauser-Horne-Shimony-Hot (CHSH)	S3	1
	Cat States	S4,S9	2
	Vacuum States	S18	1
	Cluster States	S4,S7,S9,S10,S13,S18,S23	7
	Brown State	S4,S23	2
	Coherent States	S9	1
	High-Dimensional Entangled States	S16	1
	Entangled States	S2,S3,S7,S9,S10,S11,S12,S15,S16,S18,S19,S21,S24	13
	W-tates	S10	1
QT Gates	CNOT	S2,S7,S9,S10,S11,S12,S14,S15,S18,S23,S27	11
	Qubit	S1,S2,S5,S7,S9,S10,S11,S12,S14,S15,S18,S19,S20,S21,S24,S26	16
	Pauli	S2,S3,S5,S9,S11,S12,S15,S18	8
	Toffoli (CCNOT)/Deutsche	S12	1
	Phase Shift	S2,S9,S11,S15,S18,S23,S27	7
	SWAP	S1,S4,S9,S11,S15,S18,S21,S27	8
	Fredkin (CSWAP)		0
	ISING(XX)		0
	Hadamard	S2,S9,S11,S12,S15,S18	6

2.3.4.1   Primary study summary

S1 present an Intracity Quantum Communication via Thermal Microwave Networks protocols implemented with superconducting circuits that enables the transfer of quantum states over distances of about 100m via microwave transmission lines, this experimental realization introduces new possibilities for the implementation of intracity WAN quantum communication networks based on microwave technology only. The study looked at point-to-point, which may need to be extended to point-to-multipoint. **S2** represented the realization of freespace quantum teleportation using a repeater with ground-based and satellite based transmitters. The technology shows that it has reached maturity for satellite and low-distance ground communication. **S3** produced an experiment that was realized using multiphoton entanglement in freespace quantum teleportation. The distance has been reported to have increased by two orders of magnitude. The two-photon pair over two-link freespace optical channel to two receivers on a 100km separation, successfully demonstrated presenting a way to have these findings tested on a WAN setup to ascertain its reliability for commercialization. **S4** the DSQC protocol is shown to be unconditionally secure and it can be implemented using quantum states that can be generated experimentally in laboratories, this protocol opens up the possibility of realizing secure transmission without relying on a generation of public or private keys.

S5 SDQC framework extended to point-to-point quantum communication that opens a way for its use in quantum communication networks. The layered down approach of Hardware, Software and middleware opens up opportunities in computer science, information and communication technology to simulate and test QT techniques and analyse the effectiveness of the protocols. **S6** the article present experiments for the realization of quantum memory devices that can be used for quantum repeaters/relay stations. The need for realising hybrid protocols by combining light to matter can be realised. This opens up opportunities for long distance communication applying hybrid protocols that can easily integrate light to matter and vice versa. **S7** Hybrid quantum teleportation realised through the combination of DV and CV presents new methods for realising optical QIP development using hybrid protocols. Hybrid technologies leads to universal qubit QIP processed by cluster states. **S8** study introduced a highly-efficient multi-fold SNSPDs photon based measurement paving a way towards advanced "quantum communication systems" which are based on multi-photon quantum states i.e. Greenberger-Horne-Zeilinger state and the cluster state which operate over optical fibre communication.

S9 Article analysed possible applications and implementation of QT across various techniques, listing all pros and cons as well as limitations and future use with the best applicability. No one method accomplished the set criteria to be the best possible solution, however, the combination has been presented that uses the best technologies that will lead to the realization of secure QT infrastructures. **S10** the study presented a bi-directional quantum teleportation (BQT), a bidirectional quantum secure direct communication (BQSDC) scheme is presented in which none of the users could read out the secret message without co-operating the other one through the use of intermediary. **S11** the study describes how students can easily implement quantum information protocols, and in particular a QT protocols using the IBM QE interface. QT with superconducting qubits can now be tested by any person interested in quantum information, and more generally, in quantum mechanics, be able to test the protocols and prove the theoretical protocols effectiveness and reliability.**S12** the study demonstrates a potential for realization of the bidirectional imperfect QT with a single Bell state. It heavily relied on the use of quantum random trigger qubits.

S13 the study demonstrates a tripartite scheme for probabilistic teleportation on a single qubit state in which the state teleported does not loose information. Security attacks were examined and found the scheme to be secure. **S14** a protocol for a quantum repeater network which allows for far reaching distances and higher secret key rates implementable using today's technology was presented. It is found that the elementary links' fidelity is not influenced by photon loss, nor detectors which does not count photon number perfectly. **S15** the study presents QuTiP as a technically sound framework, in that it is able to reproduce several published findings, and that it saves significant program design time due to its large library of pre-programmed functions. The tool can reproduce published results related to QT when imperfect resource states are used, as well as graph-related metrics, such as fidelity, average fidelity, concurrence, and purity. **S16** the study used twisted photons for fibre based high-dimensional quantum communication. Superposition states of different OAM modes have been generated, transmitted and detected in the experiment.

S17 the study presented a software solution which compensates for polarization-dependent loss (PDL) for silicon photonics QKD, thus enabling a low-cost high-speed QKD transmitters based on silicon photonics. **S18** The use of both CV-QKD and DV-QKD to highlight the concept of Satellite QT based on Micius satellite. Various quantum channels freespace optics (FSO), atmospheric channels etc. analysed and presented with advantages and disadvantages. **S19** The four-particle genuine entangled state improves with the combination of dense coding improves eavesdropping detection. Bell

states preparation from receiving party guarantees no leak to an intruder. Bell states secure message can be re-used while improving detection time. **S20** secure quantum data locking can be used to obtain secure communication against an intruder with time-limited quantum storage.

S21 distribution of polarization qubits and entangled photons over seawater channel, argued to introduce a limited disentanglement and depolarization, which the feasibility of quantum communication and quantum cryptography in free-space seawater can be verified. **S22** integration of SDN into the "quantum cryptography communication" network will improve the management of quantum network and control of quantum channels and classical channels for Layer 2 data centres, opens a wide area of interests to the WAN. **S23** the controlled secure quantum direct communication has potential to bridge the gap in WAN data transmission networks. Can be applied in SDN to implement the controllers. **S24** The use of QT protocols such as CV-QKD has an advantage on security with its use of key distribution and teleportation combination.

S25 the use of current urban fibre-optic infrastructure together with QKD and secure data transmission opens-up new possibilities for their wide deployment on the WAN for data centres. **S26** Article focuses mainly on QKD on LEO satellite with Nano technology and entangled photon scheme, though it looks promising and having an advantage to bridge the gap. The experiment and techniques used are within reach of current technology and less costly. **S27** the controlled bidirectional secure quantum direct communication (CBSQDC) has potential to bridge the gap in WAN data transmission networks. It can be applied in SDN to implement the controller. S28 the QCT scheme has potential to bridge the gap in the WAN transmission, however, the limitation identified by Chou, Y. et al. casts doubts on its feasibility.

2.3.4.2 Primary study categorization summary

The primary studies were further grouped, categorized based on the technologies, protocols they each present and describe. The study found that many of the articles inter-share protocols, while others go further by describing the current data transmission infrastructure they use. Other articles mainly focused on the protocols that are either in theoretical principles, while others are of a conceptual nature. The categorization each describing a unique concept in which an application of its presentation may assist in the building of secure QT infrastructures. These presentations may apply for abstract concepts of QT, while others may be broken down into low-level methods and protocols on creating QT frameworks. This grouping is described below as per the data collection form used.

Error-Correction - Error correction played an important role on the majority of the articles. Making the reversible quantum gates proved to be the core in QT to ensure data is not lost or leaked. A total of 15 articles focused on the importance of error correction. **Data security** - More than half of the articles emphasized the need to ensure security during transmission, this will ensure communication between data centres and cloud technologies is secure building a case for secure QT infrastructure implementation. A total of 15 articles confirmed data security as the core in QT realisation. **Transformation** – quantum transformation had multiple sub-categories such as Single-Qubit Operation, Two-Qubit Operation, Orbital Angular Momentum (OAM), unitary transformation, Fourier transform, Multi-Qubit gates & Networks. 17 of the articles applied single-qubit operation. We can observe that this transformation type has gained more focus and practical implementation; it was followed by two-qubit operation and unitary transformation each having a total of 4 articles, these approaches lead to new opportunities for QT transformation. Multi-qubit gates had 2 articles, while the other transformations had 1 to zero coverage.

Quantum technology - quantum technology was further broken down into photonic qubits, nuclear magnetic resonance (NMR), optical modes, atomic ensembles, trapped atoms, and solid state. Within the sub-categories photonic qubits with the use of both CV and DV and hybrid approach gained more attention with a total of 15 articles, it was followed by the optical modes that had a total of 10 articles; solid state came third having a total of 6 articles. The lower categories were NMR with 2 articles and lastly atomic ensembles and trapped atoms each having only one article. **QT- Approach** – the approach has been sub-categorized into Qubit / Discrete Variables (DV), Continuous Variables (CV), Hybrid protocols. Both DV and CV each had a total of 11 articles. Hybrid approach had 4 articles, though it has been proved to be increasingly gaining more attention and realization, bridging the GAP between CV and DV. **Methods/Protocols** – the protocols were sub-categorized into SDQT, DSQC, Super Dense Coding, SDQC, CQSDC, CBQSDC, QCT, BQCT, BQT, QKD, Deterministic and Non-deterministic. In these sub-categories, deterministic QT had 11 articles followed by QKD with 9 articles, probabilistic and QCT had 6 articles, super dense coding and DSQC had 2 articles all the others had 1 or none in the articles.

Variants/substrates/techniques – this category focuses on the physical implementation of QT, it has been sub-categorized into Polarization, Single-rail qubits, Dual-rails in free-space, Time-bin, Dual-rails on chip, Spin-orbital qubits, NMR, CV light-to-matter, CV matter-to-matter, DV light-to-matter, DV matter-to-matter, Trapped

ions, Trapped ions & photonic carriers, Neutral atoms in an optical cavity, Frequency qubit to quantum dot, Polarisation qubit to rare-earth crystal, Superconducting qubits on chip,Nnitrogen-vacancy centres in diamonds. In this sub-category polarization had 12 articles, it has been realised in the lab and in practice, it has been followed by super conducting qubits on chip with 9 articles Superconducting qubit techniques have made it through to realization in practice and simulated experiments making them good candidates for simulating QT on classical computers. Polarization qubit to rare-earth crystal have gained focus in the research community with more experiments and realization in the laboratory it had 6 articles, followed by time-bin with 5 articles, CV light-to-matter had 4 articles, followed by single-rail qubits and spin-orbital qubits each with 3 articles, all other substrates had 2 articles and others had only one article. **WAN Infrastructure** – this category has been sub-categorized into Satellite, Fibre optics, SDN/Controller, Freespace Optics, and Microwave. In this sub-category both Fibre optics and freespace optics had 10 articles followed by Software Defined Networks (SDN)/Controller with 6 articles, Satellite had 5 articles and lastly Microwave with 3 articles. This sub-category on the WAN infrastructure proved that QT can be realized in practice. Fibre optics infrastructure has proven to be realizable for MAN and support QT protocols. Freespace optics has proven to be realizable and support QT protocols paving a way for its low-cost alternative WAN infrastructure to be deployed across DC's. SDN have been proven to be realizable for QT and paving a way for applicability Cloud and Data centres that will eventually lead to quantum internet applicability, Satellite infrastructure over the WAN has been realised for QT and in process of rigorous testing for commercialization, Microwave technology looks promising for MAN deployment however still needs more proven results for its applicability on QT protocols.

Quantum Channel – this category has been sub-categorised into Thermal Channel (TC), Classical Channel (CC), Quantum Channel (QCH), Entanglement, Sea water, air-core fibre, Bosonic, LOCC, Unidirectional, and EPR. In this sub-category QC had 16 articles, followed by entanglement and CC each having 12 articles, EPR followed with 11 articles, LOCC linear channels had 4 articles, Bosonic, TC and Unidirectional channels each had 2 articles, and lastly sea water and air-core fiber each having one article. **Entangled States** – this category has been sub-categorised as BELL, Greeberger-Horne-Zeilinger (GHZ), GHZ-like, Clauser-Horne-Shimony-Hot (CHSH), Cat States, Vacuum States, Cluster States, Brown State, Coherent States, High-Dimensional Entangled States, Entangled States, W-States. In this sub-category BELL states had 19 articles, followed by Entangled States with 13 articles, GHZ and Cluster States each had 7 articles. GHZ-like, Cat States, and Brown States all had 2 articles

and all other had only one article coverage. **QT gates** – QT gates have been sub-categorised into controlled-NOT (CNOT), Qubit, Pauli, Toffoli (CCNOT)/Deutsch, Phase Shift, SWAP, Hadamard. In this sub-category Qubit gate had 16 articles followed by the CNOT gate with a total of 11 articles. SWAP and Pauli gates each had 8 articles, followed by Phase shift gate with 7 articles. Hadamard had 6 articles while Toffoli had only one article.

2.3.5 Analysis/Discussion

RQ1: The studies as detailed in section 2.3.4.1 and 2.3.4.2 have outlined how QT enables the design and building of new frameworks and technologies to enahnce security over the WAN infrastructures. These can be summarised into the use of: quantum approach, methods and protocols, variants/substrates/techniques – that are the physical implementation of QT which is a subdivision from the quantum technology, WAN infrastructure types, the type of channels, states and quantum gates.

SRQ1: Section 2.3.4.2 under QT-approach, three sub-categories is outlined as approaches to physically implement QT, highlighting a single approach or a combination of the approaches to realise secure quantum teleportation implementation. Under variants/ substrates/ techniques, sixteen sub-categories are outlined and further broken down, these can be used to physically implement secure QT, it was noted as argued by (Ulrik L. Andersen et al., 2014; Guzman-silva et al., 2015; Guzman-Silva et al., 2017) that some of the substrates are technologies while others can be protocols. Under WAN infrastructure, five sub-categories are outlined that shows capability of QT to run on the current or enhanced infrastructure to allow secure communication over the WAN.QT has been extended in various ways that include, but not limited to all-optical QT, QT networks, single photon states QT, quantum gate teleportation, QT channels and entanglement QT known as entanglement swapping.

SRQ2: The primary studies selected have highlighted limitations across the technologies, some of the limitations are in no particular order that applies to the majority of QT approaches i.e. DV, CV and Hybrid can be listed as: de-coherence, interference, transmission loss, atmospheric absorption, refraction and multipath, freespace loss, sky or ground wave propagation and line-of-sight propagation. The QT technologies as identified by primary studies: DV (S6, S7, S8, S9, S11, S14, S15, S17, S18, S24, S26) and CV (S1, S2, S3, S6, S7, S8, S9, S14, S18, S24, S26) historically followed two complementary approaches to QT with the latest hybrid schemes (S6, S7, S9, S25) that seeks to integrate the two approaches. These approaches as identified uses different WAN infrastructure approaches such as Satellite (S2, S9, S18, S26,

S28), Fibre Optics (S2, S6, S7, S8, S9, S15, S16, S17, S25, S28), SDN (S5, S10, S22, S23, S27, S28), Free-Space Optics (S2, S3, S7, S8, S9, S14, S15, S16, S18, S28), and Microwave (S1, S9, S14). Satellite infrastructure over the WAN has been realised for QT and in the process of rigorous testing for commercialization. Fibre Optics Infrastructure has proven to be realizable for MAN and support QT protocols. SDN have been proven to be realizable for QT and paving a way for applicability to cloud and data centres that will eventually lead to quantum internet applicability. Free-space optics infrastructure have proven to be realizable and support QT protocols paving a way for its low cost alternative for WAN infrastructure to be deployed across DC's. Microwave technology looks promising for MAN deployment, however still needs more proven results for its applicability for fully implementing QT protocols. Photonic qubits (S5, S6, S7, S8, S9, S11, S14, S15, S18, S20, S21, S22, S25, S26, S28), NMR (S9,S14), Optical Modes (S2, S7, S8, S9, S11, S14, S15, S17, S18, S24), Atomic Ensembles (S9), trapped atoms (S9), solid state (S9, S11, S14, S15, S17, S20). Photonic qubits have gained more focus and momentum with more articles experimenting, based on its capability and realization in practice. NMR seems to have not had much attention as few articles and experiments are reported around this technology. Optical modes have gained more focus as they can be implemented across various approaches, methods, and channels. Atomic ensembles are proving to be of great use in teleportation and entanglement swapping, involving bosonic systems of different nature that help enhance hybrid entanglement. Trapped atom technologies are still going under rigorous testing though have proven to be applicable into MAN networks through microwave infrastructure. Solid state technology has proved to be reliable and can be used in quantum circuits and quantum repeaters and allows use of hybrid protocols.

SRQ3: There seems to be no particular technology as a standalone that can satisfy all the requirements however, from the studies we have learnt that photonic qubits and optical modes are leading technologies in terms of WAN transmission, though they need to be strengthened by technologies such as solid state, trapped atoms and atomic ensembles for hybrid entanglement in order to enable quantum repeaters to extend the distance of coverage. S9 and S18 went into more detail outlining the application of each of the technologies for a best case scenario. We also argue that SDN has potential to bridge the gap in secure transmission and in implementation especially for cloud and data centre technologies, SDN technologies through open source have proved to provide a great framework to design, develop and test QT protocols and its theoretical underpinnings. The tools presented by SDNs afford us an opportunity to simulate QT to prove the theoretical principles proposed within various articles and conference proceedings.

2.3.6 Conclusion

A thorough study has been conducted on quantum teleportation in order to evaluate its capability, applicability, reliability and effectiveness in providing security for data during transmission for data centres over the WAN. The primary studies have indicated that indeed quantum teleportation is effective in providing security during transmission. Various protocols, techniques and physical substrates have been presented that outlines how such a technology can be implemented in practice or in simulations to evaluate its capability. Across all the studies it is evident that no one method is able to cater for all relevant scenarios, however it was prevalent that the use of photonic qubits as well as optical modes have excelled in bridging the gap on the WAN and also proved to be usable with integration to other technologies, like solid state systems and trapped atoms, in order to enable quantum repeaters and realise its applicability and reliability.

We have seen, as outlined in the evaluation, as well as categories in the data extraction form that QT comes in multi-facets which introduces a need to develop a generic quantum teleportation framework that can be used whenever a need arises, to implement quantum teleportation technologies either in academics or any industry. This initiative will bring more value into institutions of higher learning as QT has proven to be the future of secure communication. The study has also identified gaps where the use of SLR with regards to quantum teleportation within quantum physics, computer systems and information technology disciplines is low, making this study one of the attempts in addressing this gap. The study concludes, by highlighting a gap argued by Humble (2014) that states "protocols have been proposed, however, their realisation is still a challenge." This argument introduces a need for simulating such protocols to evaluate their capability and realisation in practice.

2.4   Conclusion and summary

Frameworks and definitions are replete in the quantum information literature. However, mostly theoretically based with less focus on the broader quantum communication or QT framework coverage, the QT theoretical principles proposed in the literatures are argued to have not been adequately realised in practice, further widening the gap for these QT protocols to be of wider adoption. These gaps make QT frameworks coverage weaker and therefore requires practical implementation or simulations to prove/disprove their submissions. An established body of knowledge within the fields of computer systems, quantum physics and QIP are growing, in relation to proving the results of the quantum information theory principles which will assist in analysing the effects of QT to securely transmit information over the WAN.

CHAPTER THREE
RESEARCH METHODOLOGY

Methodological Approach for Quantum Teleportation

In chapter one, the research problem has been identified, chapter two detailed the available Quantum Teleportation Infrastructures and their methods. This chapter details the research design and methods used for the study.

3.1 Introduction

The purpose of this chapter is to outline the research design, methods and the approach employed in the research. The research design is described as the blue print of a research project and execution of the design, and the construction process using methods and tools as the research process (Babbie & Mouton, 2001). The research design focuses on the specific outcomes of the planned research study. The process and methodology to follow is therefore chosen in order to support the significance of the outcomes and the results. With this said, the underlying philosophical belief of the research, the approach and its strategy, as well as the research design and proceeding methodology needs to be detailed.

Upon discovery of an existing problem that requires a solution or better solution than currently available, a research may be initiated. This research aims to investigate the effect of QT on the improvement of DC to DC communication security on the WAN for OSI Layer 2 technologies, in order to propose a framework for their implementation in South Africa. A DSR paradigm was therefore selected for this study.

Section 3.2 presents the research process followed. Section 3.3 outlines the research philosophical standing. Section 3.4 justifies the use of DSR as a paradigm and approach. Section 3.5 to 3.6, the research plan is presented in detail, as well as the general discussion of design research strategy, approach, data collection and data analysis methods based on the literature. Section 3.7 details the DSR artefact assessment criteria. The strategy of design research used is discussed, Section 3.8 summarises the chapter.

3.2 Research Process

The study adopted DSR model process proposed by (Vaishnavi & Kuechler, 2015b) that is an enhancement from the model originally designed by (Takeda et al., 1990) and that was also enhanced by (Hevner, March, Park, et al., 2004), it is applied into DSR by (Vaishnavi & Kuechler, 2015c; Kuechler & Vaishnavi, 2008). This DSR methodology was used as the primary guiding approach in the development of the Secure QT-Framework, as illustrated in the figure below.
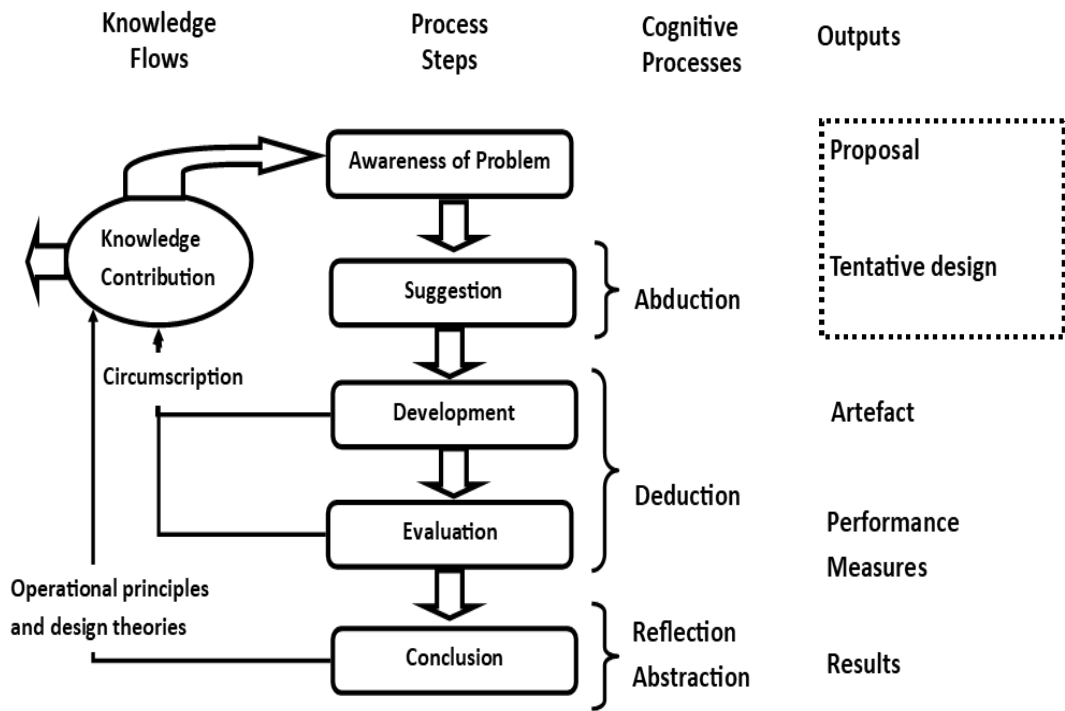
Figure 3.1: DSR process model
proposed by (Vaishnavi & Kuechler, 2015b)

The generic DSR process consists of the following five iterative steps below:

a. **Awareness of problem phase -** This is the phase in which a research problem is defined and refined in further iterations/cycles. The problem awareness can originate from several sources such as new developments in the industry or academia.

b. **Suggestion phase -** The possible design or solution is suggested with regards to the research problem identified by drawing on relevant existing knowledge or theories within, or from reference disciplines. Outputs may include a proposal for a prototype, design guidelines or envisaged solution, etc.

c. **Development phase -** This phase involves the building of the artefact which includes the design and creation of the artefact as the possible solution to the problem. The solution may be partial, requiring further iterations, or may be a complete solution.

d. **Evaluation phase -** Phase involves the appraisal of the artefact against specified assessment criteria. Quantitative and qualitative evaluation methods could be used to clarify deviations from the expected behaviour of the artefact. It also involves an analytic sub-phase, where the researcher makes the hypotheses about the behaviour of the artefact. The learnt evaluation results from the development phase are feedback to the next iteration of the design process. Further evaluation methods detailed in section 3.4.3.

e. **Conclusion phase -** This phase marks the end of a research cycle and it ends with the building of a satisfying, though not necessarily optimal, artefact. The researcher also reflects on the research process to determine the lessons that can be learnt enabling contribution to the body of knowledge. The outcome of the research is communicated to the relevant parties.

The circumscription happens when results from the evaluation triggers another cycle of repetition based on knowledge gained during the development of the artefact and feedback to another iteration of awareness and/or suggestion (Vaishnavi & Kuechler, 2013; Gilliland, 2013; Adebesin & Kotzé, 2018). This forms a unique knowledge of DSR that can be gained through "knowing through making." According to (Vaishnavi & Kuechler, 2013; Gilliland, 2013; Adebesin & Kotzé, 2018) the circumscription phase supports the contribution to the body of knowledge, typically comprising of operational principles and design theories. (Adebesin & Kotzé, 2018) specifies ways of doing research in a reproducible manner.

The cognitive processes involved in the DSR process are steps adopted from (Vaishnavi and Kuechler, 2013; Gilliland, 2015) described as:
   a. During the *suggestion phase*, solutions to identified problems are abducted from existing knowledge and/or theory of the problem domain.
   b. During the *development and evaluation phases* existing knowledge and suggestions are used in a circumscription process attempt to solve a problem. Deduction refers to the "understanding that could be gained from the specific act of construction" and evaluation of artefacts (Vaishnavi et al., 2013).
   c. In a *conclusive phase*, reflection and abstraction are used to make a knowledge contribution of new or updated designs - and operational principles and theories.

3.3   Research Philosophy

A research philosophy is defined as a system of belief in which data about a phenomenon should be gathered, analysed and used. A research paradigm is described as an underlying philosophical view of the world by a group of people about the way in which a phenomenon should be conducted by (Oates, 2006; Oates, 2009). In this study "behavioural science" paradigm is used to develop IS theory to provide truth and DSR is used to design and develop artefacts to give utility. (Hevner & Chartterjee, 2010) argues that it is possible to combine paradigms when research objectives call for it. The information and communication technology is termed as a pre-paradigmatic or multi-paradigmatic discipline based on IS.

There are four primary philosophical groundings classified and described in IS and IT as discussed below:

a. *Ontology* is associated with whether social entities should be perceived as objective which portrays a view that objects to persist in reality, external to actors or subjective, which is concerned about phenomenon which emerge from perception and consequence of actors concerned with their existence (Checkland & Scholes, 1999; Dietz, 2006).

b. *Epistemology* can be described as the acceptable knowledge of a particular area of study. For example (Vaishnavi & Kuechler, 2013) describes in design science research an epistemology of "knowing through making" which outlines a relationship in context between researcher and object of construction.

c. *Methodology* can be described as an investigation of impact of a development or construct in its context of use (Gilliland, 2014).

d. *Axiology* is concerned about values of a researcher in relation to the environment of social study (Babbie & Mouton, 2001; Adebesin et al., 2011; Vaishnavi & Kuechler, 2013).

The above philosophical approaches, allows a researcher to decide which belief assumptions to adopt, (Adebesin et al., 2011) summarised are the four belief assumptions as discussed below:

a. *Positivist research (PR)* – described as "true knowledge that may allow the prediction of behaviour of some aspect of the phenomenon". It is a repeatable study which may contain a defined independent and dependent variable. Experiments and collecting quantifiable data are typical methods employed. Studies are evaluated quantitatively and their results are recorded critically and may be generalised (March & Smith, 1995; Myers, 2009; Bhattacherjee, 2012).

b. *Interpretive research (IR)* – aims to explain how people conceptualise the world. When different groups or cultures are examined, several realities are recognized. In the research process, the IRs are not neutral and are expected to recognize their involvement and influence (Gilliland, 2014; Adebesin et al., 2011). Typical example of qualitative methods applied includes case studies, interviews, observations and action research in which the focus is on understanding the context (Oates, 2006; Myers, 2009; Adebesin et al., 2011; Bhattacherjee, 2012).

c. *Critical research (CR)* – seeks to control or improve situations. The researcher questions cultural and prevailing political as well as power relations in a social settings (Gilliland, 2014; Adebesin et al., 2011). Typical examples of qualitative methods employed are ethnography, action research and case studies (Oates, 2006; Myers, 2009; Adebesin et al., 2011).

d. *Design science research (DSR)* –defined as "*a research paradigm in which a designer answers questions relevant to human problems via the creation of innovative Artefacts,*" (Hevner & Chatterjee, 2010) therefore giving new knowledge to the body of scientific evidence. The artefacts are useful and fundamental in understanding the issue (Gilliland, 2014).

The coloured blocks represent the scope of my research as outlined below, the table is adopted from the matrix created by Adebesin (2011:310) describing the four philosophical paradigms.

Table 3.1: Philosophical assumptions of the four research paradigms
Adapted from (Adebesin et al., 2011:310; Vaishnavi et al., 2013)

RESEARCH PARADIGMS	PHILOSOPHICAL ASSUMPTIONS			
	ONTOLOGY	EPISTEMOLOGY	METHODOLOGY	AXIOLOGY
Positivist	- Single, stable reality - Law-like	- Objective - Detached observer	- Experimental - Quantitative - Hypothesis testing	- Truth (Objective) - Prediction
Interpretive	- Multiple realities - Socially constructed	- Empathetic - Observer subjectivity	- Interactional - Interpretation - Qualitative	- Contextual understanding -
Critical/ Constructionist	- Socially constructed reality - Discourse - Power	- Suspicious - Political - Observer constructing version	- Deconstruction - Textual analysis - Discourse analysis	- Inquiry is value-bound - Contextual understanding - Researcher's values affect the study
Design	- Multiple, contextually situated realities	- Knowing through making - Context-based construction	- Developmental - Impact analysis of artefact on composite system	- Control - Creation - Understanding

The DSR research paradigm was selected for this study. DSR as described by (Hevner, March & Park, 2004) needs a creative, purposeful artefact to be produced for a particular problem domain. In order to build into the knowledge contribution, the artefact is required to either solve a problem not yet solved, or provide an effective solution. Ontologically the design science researcher is involved in the research through multiple contextual situations. As the research progresses through more than one circumscription phase, the researcher is challenged with an epistemology of gaining knowledge in the process of construction, acknowledging and accepting that context affects the process. In this research, the engagement with the literature was to gain an understanding of secure transmission of information in the context of Layer 2 back-haul transmission for WAN technology in Data Centres.

The research paradigm employed in this study, namely DSR is described in more detail in section 3.4.

3.4 Design Science Research (DSR)

3.4.1 What it DSR

The term design science research (DSR) originated from design research (DR). DR has a long standing history and a broader spectrum spanning all design fields, however more importantly, doesn't have the defining feature of DSR: "learning through building artefacts" (Vaishnavi & Kuechler, 2004). According to (Venable et al., 2016) DSR is a research that "invents a new purposeful artefact to address a generalised type of problem and evaluates its utility for solving problems of that type." DSR is an accepted research paradigm and an approach in the Information Systems (IS) field, aiming at developing purposeful IT artefacts and knowledge about the design of IT artefacts (Peffers et al., 2012; Gregor & Hevner, 2013).

With this said the guidelines for DSR assessment by (Hevner & Chartterjee, 2010) as described below are adopted for this research:

Table 3.2: Guidelines for DSR

Adapted from (Hevner et al., 2010:12)

Guideline	Description
Design as an artefact	DSR research must produce a viable artefact
Problem relevance	The objective is to develop a technology-based solution to a relevant business problem
Design evaluation	The use of well-executed evaluation methods to test utility, quality and efficacy of an artefact
Research contributions	An effective DSR must provide clear and verifiable contributions in the areas of design artefact, design foundations, and/or design methodologies
Research rigour	DSR relies upon the application of rigorous methods in both the construction and evaluation of the design artefact
Design as a search process	Utilise available means in the search for an effective artefact and solution to a problem
Communication of research	Effective presentation of DSR to both technology- and management-oriented audiences

The artefacts referred to in this context are those that are artificially made objects together with their processes as outlined by (Goldkuhl, 2002). Four key components

and their definitions have been elaborated by (Venable & Baskerville, 2012) as stated below:

a. *Purposeful artefact:* Characterized by design for a specific human or objective purpose. The artefact may be a process, a system, a strategy, a methodology or a mixture of any of these. A purposeful artefact may contain both, product and its associated process (Adebesin & Kotzé, 2017). E.g. a framework artefact may have both, the framework itself (product) as well as a method for its application.

b. *An invention:* Requires development, change in model, and adaptation. There is no need to create technology from scratch.

c. *Address a generalised problem type:* The resulting artefact and process to create it is such that it can be applied repeatedly to solve various problem type occurrences, not just a specific issue.

Evaluation: Assessment of the resulting artefact provides assurance that it can solve the type of problem for which it was created. This is proof of the usefulness of the artefact.

3.4.2 DSR Artefacts

(Hevner & Chatterjee, 2004) as well as (Adebesin & Kotzé, 2017) details the types of foundational artefacts in the field of IS that may be created or produced during the DSR process as per Figure 2. The forms taken are described in detail below:

a. *Constructs* according to (March & Smith, 1995; Hevner & Chatterjee, 2004) consists of vocabulary that describe a given problem or solution that presents particular discipline by a group of researchers with shared language and knowledge.

b. A *model* according to (March & Smith, 1995; Hevner & Chatterjee, 2004) normally emerges when the DSR process is conceptualised, it contains relationships between constructs. Models can also be an approximation or a condensed description of a particular problem or solution.

c. A *method* is the structured mechanism or methodology for executing a particular task (March & Smith, 1995; Hevner & Chatterjee, 2004); the methods can also be viewed as an action plan to achieve a target.

d. A *framework* Provides a standard structure for achieving the desired outcome (Adebesin & Kotzé, 2018). A Framework include a model and related methods for using or implementing the model (Bart Verbrugge, 2016).

e. An *instantiation* is described as an actualization a new design, system, process or framework; offering a way of demonstrating the viability and usefulness of

constructs, designs or methods for a particular environment (March & Smith, 1995; Hevner & Chatterjee, 2004).

f. *Better design theories* are artefact objects identical to the experiments in natural science studies (Vaishnavi & Kuechler, 2015b). The thought process of abstraction and reflection promotes the introduction of information which can lead to better theories (Vaishnavi & Kuechler, 2015a; Adebesin & Kotzé, 2018).

According to March and Smith (1995:253), The development, production and analysis of an artefact is a common research practice in IT and computer science study and can be expanded to include the hypothesis building and reasoning testing practices used in natural science research. The theories must explain How and why IT systems work within their operating environments and the research should attempt to justify the theories March and Smith (1995:255), Hevner shares a similar view and expands by saying The design and creation of artefacts not only enhances the ability to solve individual and institutional challenges, but also facilitates the concept formulation on the effect, execution and use of artefacts.

In this study, the primary focus is on the building and evaluation of a framework artefact.

3.4.3 DSR evaluation methods for artefacts

DSR evaluation according to Hevner et al. (2004) is described as a fundamental part within the DSR process which enables researchers to gives ground to the utility, trait and effectiveness of an artefact. Various approaches have since been identified by (Vaishnavi & Kuechler, 2013; Gilliland, 2013; Adebesin & Kotzé, 2018) which can be used in the evaluation of DSR artefacts, namely: *Observational /Case Study approach*, *Analytical, Experimental evaluation* and *Descriptive evaluation*.

a. The observational method may take the form of a case study where an in-depth analysis of the object is performed in a suitable environment. It also includes field studies in which various contexts control the use of the object.

b. The A*nalytical evaluation* according to Hevner et al. (2004) may extract one of four methods as described below:

   i. *Static analysis*, investigates the artefact's configuration for the existence of predefined qualities.

   ii. *Architecture analysis*, measures the degree to which the object blends into a given technological IS architecture.

   iii. *Optimisation analysis*, demonstrate the artefact's essential optimum characteristics.

iv. *Dynamic analysis*, provides an examination of the artefact's diverse qualities.

c. An E*xperimental evaluation* may take a form of controlled experiment context in which the artefact is tested within a controlled environment such as a laboratory or by simulating the artefact's function using artificial information.

d. *Testing* may take the functional testing form where the artefact interfaces are checked for any fault or structural testing where certain artefact routes are selected to determine their coverage rate. (Adebesin & Kotzé, 2018)

e. *Descriptive evaluation* may be achieved through informed arguments where current knowledge is utilised to build a convincing argument about the utility of the object or by creating examples around the artefact to demonstrate its usefulness (Adebesin & Kotzé, 2018).

The evaluation technique selected for the SecureQT-Framework artefact is both the *Descriptive* and *Experimental*. SecureQT-Framework artefact takes the form of simulated reality to execute artefact with artificial data, and involves the use of *hypothetical scenarios* to get around issues of real-world access to applications, while still having convincing facts and being able to build comprehensive object scenarios to demonstrate its usefulness. Using Scenarios is a good avenue to pursue as contrived scenario grounds the artefact in a specific context without relying on an indefensible generalization.

3.4.4 DSR Knowledge Contribution

An active DSR should make clear and verifiable offering in the fields of artefact design, design foundations and/or design methods (Hevner & Chatterjee, 2010). DSR rely on the use of robust methods which are achieved by drawing from various domains. "IS research is accomplished by raw materials provided for in the knowledge base, prior results of IS research from reference disciplines provides [constructs] in the development phase. Methodologies provides guidelines employed in the evaluate phase" (Hevner et al. 2004:80). According to (Iivari, 2007; Gaß et al., 2012) the knowledge contribution in DSR falls into three main categories namely:

a. *Conceptual knowledge* may refer to typologies, taxonomies, concepts, classifications and conceptual frameworks, etc.(Adebesin & Kotzé, 2018).

b. *Descriptive knowledge* details of "what" knowledge of natural phenomena and the laws which guide them. These may involve evidence of experience, statistical regularities, ideas, hypotheses (Van Aken, 2005; Iivari, 2007; Gregor & Hevner, 2013; Adebesin & Kotzé, 2018).

c. *Prescriptive knowledge* details of "How" knowledge of man-made artefacts, including knowledge of design processes, knowledge of product design,

methods, etc. Which is designed to solve specific problems (Van Aken, 2005; Iivari, 2007; Gregor & Hevner, 2013; Adebesin & Kotzé, 2018).

In order to tackle the SecureQT-Framework it is vital to understand the form of an appropriate response and how it can be used in practice. The main issue is the usefulness rather than the truth. With this said, this study was primarily concerned with the construction of a framework that is beneficial for professionals and scholars as opposed to the exploration of the fundamental facts about the world. Hence the applied nature of the knowledge acquired. This research therefore follows a structured approach to develop and evaluate a framework in order to ensure it is rigorous and relevant. This study agrees with Hevner et al. (2004) as he argued that IS research "needs to be rigorous to contribute knowledge to the knowledge base and relevance for application in the appropriate environment". Therefore this study adopts both *Descriptive* and *Prescriptive Knowledge* as argued by Gregor and Hevner (2013:343) that knowledge in DSR should comprise both types.

This is done through a comprehensive review of articles, books, papers, conference proceedings, dissertations, theses, documents and online media used to examine information relevant to this research. Since I need to map the elements of these foundational knowledge into the SecureQT-Framework from the research problem it is clear that, I'm dealing with two subfields of information systems: Information transmission and information security. The part of knowledge base to be considered from the reference discipline in order to provide new perspective to the data transmission security problem that will lead to the development phase of the artefact is the information theories (computer science and quantum physics). It is argued by (Humble, 2007; Pirandola et al., 2015) that Quantum teleportation is a subfield in quantum information science, which is emerging as a new framework to develop Information and Communication Technologies (ICT) that works as per the laws of quantum physics and information theory. It is further argued that, by analysing and exploiting specific features of computational models by combining physics and computer science perspectives, QT establishes and presents a framework for designing protocols that are unconditionally secure and enables the development of ultra-secure communication, overcoming the limit of conventional technologies (University of Edenburg, 2015).

Descriptive knowledge from hypothesis and models in reference disciplines i.e. (Quantum Physics, Computer Science and Information Theory) were used to provide the foundation for association between my research and existing knowledge. The

generic quantum teleportation protocol by Bennett et al (1993:1895) applied as framework reference, is an example of the prescriptive information used in this study. A thorough literature review was conducted, in which studies were analysed and useful information was extracted.

3.5 Employing Design Science Research

According to Adebesin and Kotze (2018:5) various authors emphasis on various aspects of published DSR articles such as: "processes/approaches, guidelines for use of DSR, DSR outputs or artefacts, evaluation methods for DSR artefacts, review of different forms of artefacts emanating from a selection of DSR studies and ethical principles that guide the conduct of DSR". Based on the adopted model three design research cycles are prominent as displayed in the figure below.
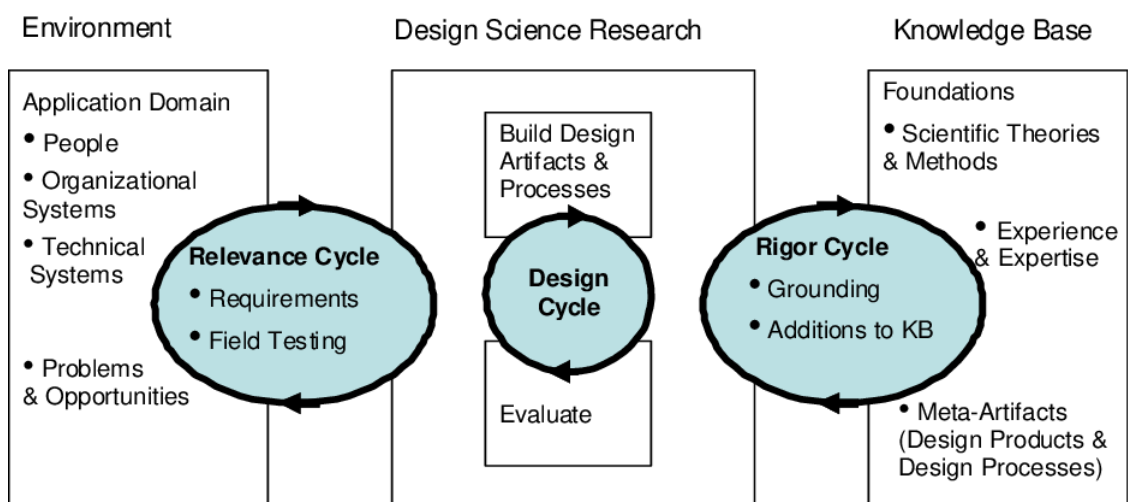
Figure 3.2: Design research cycles and research relevance and rigour
Adapted from (Hevner et al., 2010:16)

- In the Relevance Cycle the research problem is outlined or explains the need of the research and the environment.
- The Rigour Cycle uses existing knowledge or design theories, methods, product design, design processes, artefacts, experiments and expertise to provide a rigorous basis. In this study being rigorous is achieved by employing theories from reference field such as quantum physics, computer science.
- The design cycle a thorough testing and evaluation is used where problem statements or requirements are revisited and enhanced.

This research scope is limited to DSR output/artefacts as well as the process followed during the design and development of the framework as adopted from Hevner et al. (2004).

3.6 Research Design/Strategy

Now that the design science approach and the needs for the research have been outlined, I now present the overall design of the research. I initially presented the philosophical grounding of the research, and then detailed the five empirical phases on how they meet the requirements for doing design science. Lastly the proposed research design is discussed following the guideline by Hevner et al.(2004) to argue that my research design is well justified.

The research process according to Gilliland (2015:94) and (Oates, 2006) enables the analysis, explanation, justification and evaluation of artefacts. The design approach was suitable in this research as the focus was on creation of an artefact rather than intervention.

The DSR methodologies and system models suggested by Vaishnavi and Kuechler (2013) as displayed in figure 2.3, was chosen as the technique to guide the construction of the SecureQT-Framework artefact.

3.6.1 Philosophical Position

Hevner et al. (2010:11) argues that it is possible to combine paradigms when research objectives calls for it. The information and communication technology is termed as pre-paradigmatic or multi-paradigmatic discipline based on IS. With this said, design science paradigm was chosen for this research as the main paradigm to design and build artefacts that give utility with behavioural science that provide truth when developing IS theory.

Below I present the philosophical stance of the research project.

3.6.1.1 Ontology

Ontologically the focus is on the creation of a framework for the implementation of secure quantum teleportation infrastructure in South Africa, which can be used in more than one enterprise. Since this is not an action research and adopting a deductive approach in the form of a simulated reality, the process, contextual and special nature of design research (DR) had to be understood. The four DR sub-cycles contributed in the development of the Secure Quantum Teleportation Framework (SecureQT-Framework).

3.6.1.2 Epistemology

Epistemologically, knowledge gained in a sub-cycle has generated knowledge of what the next sub-cycle requires to begin. Each sub-cycle's operational context was

distinctive. Since utility is the emphasis rather than truth, the goal of evaluate/justify is appropriate. The DSR seeks to contribute in the knowledge base the kind of knowledge which is validated and useful (to practitioners and academic communities). From this viewpoint, the belief justified as true is knowledge that will work.

3.6.1.3 Methodology

Methodologically, SecureQT-Framework is developed as an artefact to be used when implementing data transmission infrastructures for Cloud and Data Centre technologies.

3.6.1.4 Axiology

Axiologically the DSR researcher understands how artefacts help to solve challenges and bring about positive change in organizations. I evaluated the imaginative use and management of the research environment in addition to knowing and monitoring the key study as well as each sub-cycle creation stage as described by (Vaishnavi et al., 2013). For this study the artefact implies an enhanced data transmission security for Cloud and data centre organisations. A framework for implementing secure quantum teleportation infrastructures was assembled after completion of the DR cycles.

This study upholds the importance of giving back to the body of knowledge in the research community; the acquired knowledge will be placed into public domain immediately, in full, without reservation. This will allow for researchers and scholars to reproduce the work without consideration to potential commercial advantage.

3.6.2 Develop Framework

The research phases are outlined in this section and also justified as to why each step is important and the reasoning for the methods chosen is illustrated. The coherence of the research design is therefore detailed as to how it fits to the requirements for DSR of Hevner et al. (2004). As stated by Hevner et al. (2004) producing and evaluating of a purposeful artefact is required in DSR for a body of work to be classified as such. (Kuechler & Vaishnavi, 2008) complement this by adding that IS research should be cumulative and novel to balance existing research where possible. This project will achieve this by taking existing quantum teleportation protocol by (Bennett et al, 1993:1895) and re-interpreting it in terms of (Humble, 2013; Pirandola et al., 2015; Pirandola & Braunstein, 2016) and further interpretation in the view of information theory. By this, the requirement for both cumulative and novel will be satisfied.

These are discussed in the following sections.

3.6.2.1 Primary Design Research Cycle

The Primary DSR cycle describes the methodology followed for the entire research process:

a. ***Problem Awareness -*** The problem awareness was established after the review of literature on security of data during transmission, where security experts and my academic supervisors mentioned the problem of Layer 2 data transmission security for data centres over the WAN. We identified that, while there are a number of mechanisms, theories and laboratory experiments around Quantum Teleportation as a potential solution, none specifically addressed the question of building frameworks to guide their implementation, utilizing generic models and methods. A need for the development of generic secure quantum teleportation model and method for Layer 2 data transmission infrastructure implementation (SecureQT-Framework) was therefore established.

   b. ***Suggestion -*** study claim was established during the suggestion process which said "it is possible to investigate the effect using QT technologies to improve security for layer 2 data centre transmission technologies to assist in proposing a SecureQT-Framework for its use".

   c. ***Development -*** The phase of development included the design and development of the artefact framework that addressed research objective 1 (RO1). This was guided by four sub-cycle phases comprised of the refinement of the model and method artefact to address research objectives (RO3) that is to "Propose a framework for the implementation of secure QT infrastructures". The development phases are explained in detail in the upcoming Chapter 4.

   d. ***Evaluation –*** in the primary design research cycle evaluation phase SecureQT-Framework was presented and evaluated against principles for framework by using a simulated experiment that is based on empirical work for its usefulness and appropriateness. The literature knowledge base was used for informed arguments in support of the results. The results were analysed on multiple contexts and the SecureQT-Framework was updated.

   e. ***Conclusion –*** in the conclusion phase, SecureQT-Framework was verified. Study results were reported to the academic audience and in the academic publications including final thesis, possible implementation for SecureQT-Framework was presented and future research prospective suggested.

3.6.2.2 Design and development of SecureQT-Framework

Four sub-cycles of the design research was completed in the design and building of the SecureQT-Frameworks Model and Method. First two sub-cycles were addressing research objective 2 (RO2 – To analyse the effect of using QT to securely transmit

information). Upon completion of sub-cycle 3 and 4 embedded within the primary design research development, SecureQT-Framework was compiled in realising of research objective 1 (RO2 – To design and develop the QT framework for use in layer 2). SecureQT Model comprised of a comprehensive list of five phases selected from the literature and mapped into sub-categories, the model and methods have been evaluated over various contexts. The SecureQT-Framework was established as a model and a proposed method of implementation to realise research objective (RO3 - Propose a framework for the implementation of secure QT infrastructures for DCs). The development phase involved:

a. Combining a foundational knowledge which is selected from IS research literature as well as the reference fields.
b. Gaining knowledge through comprehensive understanding of the scope of the problem, infrastructural background and planned usage.
c. Assess, evaluate and extend combined knowledge based on the acquired domain understanding of the literature review.

To meet the goal of being rigorous, the gathering, evaluation and synthesizing knowledge through the SLR of the relevant literature was conducted. Rigour also demands for DSR to draw from existing knowledge base which comprise of reference fields and the collected knowledge in the IS domain. To be appropriate, the research was driven by the current needs of academics and IS practitioners.

The need for both rigor and relevance were met by reviewing literature based on:

a. The important source of knowledge around methodology on current IS research comprising of conference proceedings, scholarly journals and articles, technical and other related publications in which the authors are primarily academics writing for academic audiences, post graduate students and practitioners, information theory models and theories on quantum teleportation, and information transmission and security practices. This is part of the knowledge base that this study attempts to contribute to.
b. Information Systems practitioner literature which is found in journals, whitepapers, websites and industry seminars which are practitioner oriented (Hill, 2009:31). This kind of knowledge is useful for understanding issues concerning practitioners and how they view them.

Systematic literature based on reference disciplines, which may take a form such as textbooks, seminal papers, journals, etc. IS needs to consider such information (Hill, 2009).

3.6.2.3   Conceptual Study

This phase employs the reference disciplines and IS domain knowledge (Literature review) to bear the business requirements from the first phase (systematic literature review). The result is a conceptual framework of quantum teleportation in transmission systems compliant to analysis and simulation. This involves synthesis of key insights and desperate knowledge. According to (Shanks et al., 1993) "*conceptual studies can be effective in building new frameworks and insights and can be used in the current situation or to review existing bodies of knowledge. Its strengths are that it provides a critical analysis of the situation which can lead to new insights, the development of theories and deeper understanding.*"

This is an important step to the research design, as it is here that the framework is designed and developed. The resulting utility is a framework for secure quantum teleportation which constitute a model (framework and method) together with recommendation for practitioners/academics/scholars to use for their particular systems. This artefact needs to be evaluated in order to understand its impact in practice and to contribute to the knowledge base.

This leads us to the next step which subjects the resulting artefact to justify/evaluate the phase.

3.6.3   Evaluate Framework

The technique selected to evaluate the SecureQT-Framework artefact is the *Descriptive* and *Experimental Evaluation*. The SecureQT-Framework artefact takes the form of simulation to execute the artefact with artificial data and involves the use of *hypothetical scenarios* to tackle the problem of access to real-world applications while still presenting convincing facts and constructing comprehensive artefact scenarios to show its usefulness. Using Scenarios is a good avenue to pursue, as contrived scenarios grounds the artefact in a specific context without relying on an indefensible generalization.

3.6.3.1   Simulation Study

I argue that computer simulation using randomly created artificial data, provides the best way of producing the results that mimics the real-world scenario. This is due to the fact that it is difficult to get real world QT project access, given the legal and commercial hurdles and other factors. The time and scope constraints also do not allow the examination of multiple scenarios. A laboratory environment is needed to configure the

setup for the artefact evaluation. The experiment for evaluation was made out of a virtualized environment. The virtualised environment was setup in the CPUT Engineering Building. (Dasari et al., 2015) argued that Software Defined Networks (SDN) provides a "device-agnostic programmable framework" to encode new network functions such as QT and Super Dense Coding (SDC), etc. They further argued that it provides an intelligence centralized external control plane which allows programmers to build functional networks designs and write network applications. The architecture environment for this evaluation uses Open Source tools and they are virtualized.

3.6.3.2 Evaluation by Argumentation

The final testing method and the resultant artefact should be measured against specific criteria as you cannot rely solely on a virtual study's statistical analysis of a simulated study. We have adopted the use of guidelines published by Hevner et al. (2004).

3.6.4 Data Collection

The table below summarises the data collection methods within their respective DR cycle and subsequent research objectives and sub-objectives have been addressed. This research's process of data collection can be listed as one utilizing multiple methods. By using multiple methods, a number of methods have been used to suit a range of uses (Saunders et al., 2009).

Table 3.3: Data collection

Design Research Cycle	Literature	Experiment/Simulation	Informed Arguments
Primary Cycle	Main research aim, questions and objectives RO1, RO2, RO3	RO2, RO3	RO2, RO3
Sub-cycle 1	RO1, RQ1, SRQ1		
Sub-cycle 2	RO1, RQ1, SRQ1		
Sub-cycle 3	RO2, RQ1	RQ1, SRQ2, SRQ3	SRQ3
Sub-cycle 4	RO3	RO3, SRQ3	SRQ2, SRQ3

In an exploratory study, a literature survey with the purpose of understanding the context of the research and by gaining insight into quantum teleportation landscape was employed. As highlighted in previous sections this is not an action research. There was no requirement for engagement with any organisation. Data was gathered from literature on different QT studies. A systematic literature survey was conducted to determine various QT schemes and their respective classification and categorization in support of RO1 and SRQ1. The focus in RO2 (To design and develop the QT framework for use on Layer 2 and SRQ1: What QT frameworks and protocols exist to address security challenges for DCs Intercommunication over the WAN?) were on collecting and grouping of information and opinions from different sources of literature.

Realisation and output from this phase was the identification and recognition of the need for a framework for the implementation of secure quantum teleportation in the South African context. The literature was employed to find a comprehensive list of QT techniques, approaches, methods, classifications and categorizations. More data was collected using a simulated experiment that formed the bulk for evaluating the artefact. Informed arguments were utilised in collecting information from the knowledge base in order to ground the artefact on empirical data.

3.7 Assessment of the Research Design

Hevner et al. (2010:12) created the below guidelines. I outline the guidelines and discuss how the presented research design meets them.

Table 3.4: Artefact assessment

Adopted from Hevner et al. (2010:12)

Guideline	Description	Discussion
Design as an Artefact	Design Science research must produce a viable artefact in the form of a framework, a construct, a model, a method, or an instantiation.	The SecureQT-Framework produced during the development phase meets the criteria of an artefact, as it embodies a *construct* (conceptualisation of problem), a *Framework* (description of IS behaviour) and *method* (in this case, a socio-technical method for organisational practice).
Problem Relevance	The objective of Design Science research is to develop technology-based solutions to important and relevant business problems.	Practitioners and other scholars/academics - have provided time and resources to tackling this issue which signals the extent to which they perceive the problem as vital and relevant.
Design Evaluation	The utility, quality, and efficacy of a design artefact must be rigorously demonstrated via well-executed evaluation methods.	Evaluating the artefact is by orchestrating scenarios with artificial information and decision processes with rigorous analyses on results.
Research Contributions	Effective Design Science research must provide clear and verifiable contributions in the areas of the design artefact, design foundations, and/or design methodologies.	This research project identifies a clear gap in the existing IS knowledge base around secure QT infrastructures and seeks to fill it through the careful application of the appropriate research method (Design Science).
Research Rigour	Design Science research relies upon the application of rigorous methods in both the construction and evaluation of the design artefact.	This research design follows well-founded guidelines from the IS literature for understanding business needs using the existing knowledge base (literature review).
Design as Search	The search for an effective artefact requires utilising available means to reach desired ends while satisfying laws in the problem environment.	Here, the artefact is bound by organisational norms which are secure transmission of information, and seeks to understand these and operate within them.

| Communication of Research | Design Science research must be presented effectively both to technology-oriented as well as management-oriented audiences. | The research is communicated to the wider IS community by making available the research study, its methods and approach, and findings for reproduction. It is also presented to the scholars/academia in my academic institution. |

3.8 Summary

This chapter's purpose was to provide research-related literature. The research's philosophical paradigm and underlying approach, hypotheses, design and methodology were discussed. This research project was concerned with building and evaluating a purposeful artefact a framework for the implementation of a secure quantum teleportation infrastructure in South Africa. With this emphasis on producing an artefact that is useful to practitioners and academic audience, the most suitable research design and methodology was the one employing design science as highlighted on the five aspects of importance outlined. The five step process model from Vaishnavi as well as guidelines from Hevner et al., was relevant for my scope and so I adopted their guidelines, terminology and criteria for assessment.

The three research objectives, primary research question, the three sub-research questions initiated the Primary DSR cycle with four sub-cycles of the circumscription phase of the design science research. The awareness of problem, suggestion phase, development phase, evaluation and conclusion phases were the research steps followed and outlined in the research cycles. The development phase employed a literature review (from academic and practitioner knowledge sources) the outcomes within a sub-cycle kick-started another problem awareness to initiate the beginning of the next sub-cycle. The evaluation phase proceeded with a simulated experiment for the SecureQT-Framework using artificial information, followed by a realistic analysis of the artefact and the outcomes of the simulation. A conceptual analysis synthesizing the interpretation of information systems with relevant expertise was developed within the framework itself.

A detailed research plan was described with outlined events that transpired during the design science research's primary and sub-cycles described in chapter 4, 5 and 6.

CHAPTER FOUR
DESIGN AND DEVELOPMENT OF THE SECUREQT-FRAMEWORK

Design & Development of the SecureQT-Framework for Layer 2 Infrastructure Implementation

Research design and methodological approach was detailed in chapter three. This chapter outlines the design and development of the generic framework to guide the implementation of layer 2 data transmission infrastructures.

4.1 Introduction

Vaishnavi and Kuechler (2015) five step DSR process model was utilised as the guideline for the development of the SecureQT-Framework. Figure 4.2 outlines the high-level illustration of the DSR process used to realise our research objective. The awareness of problem phase, suggestion, development, evaluation and conclusion phases forms part of the fundamental DSR cycle in which four sub-cycles were outlined in the development phase each with its own phases of "problem awareness, suggestion and development" respectively. The aim of this study was to: "investigate the effects of QT on the improvement of DC to DC communication security on the WAN for OSI Layer 2 technologies", to model and build a framework for its implementation.

Three main research objectives(RO) are defined:

1. To design and develop the QT framework for use in Layer 2 (RO1).
2. To analyse the effects of using QT to securely transmit information (RO2).
3. To propose framework for the implementation of secure QT infrastructures (RO3).

The data collection processes as they unfolded are described in this chapter to address research objectives (RO1, RO2 and RO3). Therefore this chapter outlines each of the primary DSR process cycles in more details organised as follows:

- Section 4.2 the problem awareness.
- Section 4.3 presents the suggestion.
- Section 4.4 involves the development containing five sub-phases within DSR process.
- Section 4.5 contains the evaluation
- Section 4.6 presents the conclusion
- Section 4.7 conclusion.
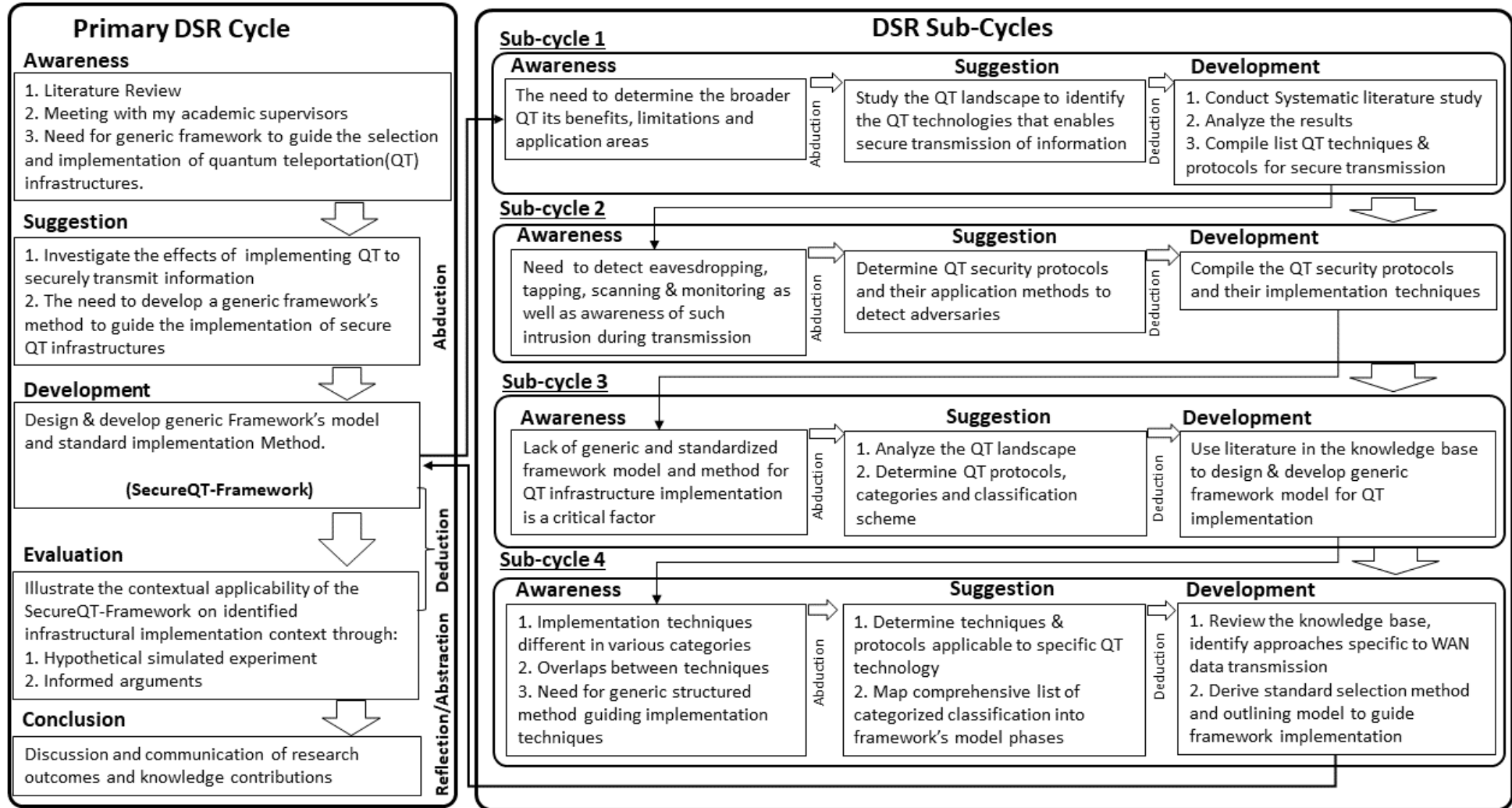
Main Design Research Activities

Primary DSR Cycle

Awareness
1. Literature Review
2. Meeting with my academic supervisors
3. Need for generic framework to guide the selection and implementation of quantum teleportation(QT) infrastructures.

Suggestion
1. Investigate the effects of implementing QT to securely transmit information
2. The need to develop a generic framework's method to guide the implementation of secure QT infrastructures

Development
Design & develop generic Framework's model and standard implementation Method.

(SecureQT-Framework)

Evaluation
Illustrate the contextual applicability of the SecureQT-Framework on identified infrastructural implementation context through:
1. Hypothetical simulated experiment
2. Informed arguments

Conclusion
Discussion and communication of research outcomes and knowledge contributions

Abduction
Deduction
Reflection/Abstraction

DSR Sub-Cycles

Sub-cycle 1

Awareness
The need to determine the broader QT its benefits, limitations and application areas

Abduction

Suggestion
Study the QT landscape to identify the QT technologies that enables secure transmission of information

Deduction

Development
1. Conduct Systematic literature study
2. Analyze the results
3. Compile list QT techniques & protocols for secure transmission

Sub-cycle 2

Awareness
Need to detect eavesdropping, tapping, scanning & monitoring as well as awareness of such intrusion during transmission

Abduction

Suggestion
Determine QT security protocols and their application methods to detect adversaries

Deduction

Development
Compile the QT security protocols and their implementation techniques

Sub-cycle 3

Awareness
Lack of generic and standardized framework model and method for QT infrastructure implementation is a critical factor

Abduction

Suggestion
1. Analyze the QT landscape
2. Determine QT protocols, categories and classification scheme

Deduction

Development
Use literature in the knowledge base to design & develop generic framework model for QT implementation

Sub-cycle 4

Awareness
1. Implementation techniques different in various categories
2. Overlaps between techniques
3. Need for generic structured method guiding implementation techniques

Abduction

Suggestion
1. Determine techniques & protocols applicable to specific QT technology
2. Map comprehensive list of categorized classification into framework's model phases

Deduction

Development
1. Review the knowledge base, identify approaches specific to WAN data transmission
2. Derive standard selection method and outlining model to guide framework implementation

Figure 4.1: Primary DSR cycle for SecureQT-Framework

4.2 Problem awareness Phase

As stated in section 3.6.2.1 the problem awareness, was confirmed subsequent to literature on security of data during transmission was reviewed, where security experts highlighted the problem of Layer 2 data transmission security for data centres over the WAN. At the meeting academic supervisors further identified that, while there are a number of mechanisms, theories and laboratory experiments around quantum teleportation as a potential solution, none specifically addressed the question of building frameworks to guide their implementation utilizing generic models and methods. This problem though it is general, however, for this research's scope the context is within the South African setting. The complex nature of quantum teleportation does not define itself within a single domain of expertise as it is multidisciplinary with various individual differences that exist. After considering the gaps identified above we were able to give grounds of a need for the development of a framework artefact with an ability to address the limitation. Therefore, a need for the development of generic secure-quantum teleportation model and method for Layer 2 data transmission infrastructure (SecureQT-Framework) was established to guide its implementation.

4.3 Suggestion Phase

As stated in section 3.6.2.2 during the suggestion phase, the need to investigate the effect of using QT technologies to enhance security for layer 2 data centre transmission technologies. The contextual focus is within the South African setting, further suggestion was to develop the generic framework to guide the implementation of secure quantum teleportation infrastructures. The intended users of the SecureQT-Framework will be any data centre agency operating within Layer 2 data transmission over the WAN.

The design objectives for SecureQT-Framework identified were:

- The framework must provide a phased generic approach model for the selection of quantum teleportation technologies to implement.
- It should provide applicable implementation guidelines and must be (inherently secure, adaptable, integrated, and dynamic).
- It should provide guidance within the knowledge base in which to find technologies to consider.
- The SecureQT-Framework should be easier to follow with limited knowledge or skill sets of the finer-details.

4.4 Development of the SecureQT-Framework

The SecureQT-Framework development contains four sub-cycles (study QT landscape, determine security protocols and application methods, analyse the QT

landscape, determine categories and classification, determine techniques and specific protocols applicable to quantum technology, mapping of the categories). Each sub-cycles contained its own problem awareness, suggestion and development phases.

The sub-cycles are discussed in detail in the sections below.

4.4.1 DSR Sub-cycle 1 (RO2): Determine QT landscape

The question for the ***problem awareness*** sub-cycle phase was how can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DCs? The first research question of the study was established (RQ1): To determine QT frameworks and protocols that exist to address security challenges for DCs intercommunication over the WAN. The ***suggestion*** the need to research the QT context was discussed in order to gain a deeper understanding of its consequences in order to identify QT technologies that enable secure transmission of information. The ***development*** phase used SLR. The SLR survey was done, data collected and evaluated, and the outcomes were assembled into a list of QT techniques, categories and sub-categories, together with their benefits, challenges and application. This led to another initialisation of the sub-cycle 2 problem awareness phase.

4.4.2 DSR Sub-cycle 2 (RO2): Determine QT Security protocols and their application methods

This sub-cycle ***problem awareness*** phase generated the question of the need to detect eavesdropping, network tapping, scanning & monitoring as well as awareness of such intrusion during data transmission.The ***suggestion*** was to study QT to determine security protocols and their application methods to detect adversaries. The ***development*** phase literature on QT security protocols and appropriate technology for their implementation were reviewed to determine the effects of QT to solve security for data transmission over the WAN. We have found that there are multiple quantum teleportation protocols that are inherently secure and can detect intrusion and other adversaries that helps secure the transmission of information. We also found that no single method can address all the requirements, either due to limitations within the technology used, or the protocols applied, or even the physical medium and infrastructure utilised. A finding on interoperability/integration between approaches also introduced a problem for standardization of the technologies. This allowed us to make an informed decision in which a comprehensive list of the protocols and their methods were compiled. The issue identified was the lack of a generic standardised model and method for implementation of the infrastructures, this led to another initialisation of sub-cycle 3 the

problem awareness phase to study the knowledge base to determine frameworks standardization.

4.4.3 DSR Sub-cycle 3 (RO1): Analyse the QT landscape for standardisation

This sub-cycle phase ***problem awareness,*** came upon realisation that there is a lack of standardized models and methods for QT infrastructure implementation, though multiple protocols and techniques exist and were compiled. We analysed the comprehensive list of protocols and techniques, a further ***suggestion*** was to analyse the QT landscape to determine the protocols and techniques categories to determine a classification scheme for their standardised grouping. Various categories and classifications were described in the literature knowledge base and possible classification for grouping was suggested. This sub-cycle ***development*** stage of the literature knowledge base was utilised in order to design and develop a generic framework for QT implementation by identifying and selecting suitable QT categories. The comprehensive list of the SecureQT model was categorised into five phases. Methods followed in other countries by researchers were investigated to identify standards to adopt, thus sub-cycle 4 the problem awareness phase was kick-started.

4.4.4 DSR Sub-cycle 4 (RO3): Map comprehensive QT classification and categories

The ***problem awareness*** phase was that multiple implementation techniques exists with various categories introducing overlaps, impacting standardization, thus a need for a generic structured model and method were identified. The ***suggestion*** phase was to determine the techniques and their relevant protocols that can be mapped into a comprehensive list for categorization and classification to form a framework. The ***development*** phase reviewed literature in the knowledge base for foundational approaches, specific to WAN data transmission technologies, through information theory and quantum information science. We derived a standard selection method and developed an experiment to simulate the applicability of QT, outlining the methods to guide our implementation, detailed in chapter 5.

4.4.5 Develop SecureQT-Framework's model and Method
4.4.5.1 Lessons from the review of standards adoption Approaches

The development of SecureQT-Framework relied more on learnt lessons within the review of the literature. The major lesson was that two complementary approaches were followed in which one relied on the discrete nature of light, while the other was on the continuous nature of light. All the approaches had their own advantages and disadvantages. However, a hybrid approach which is the combination of the two approaches was proposed and realised in practice, due to the advancement in

technology. We also learnt that quantum teleportation is a vast field with interdependencies that involves variants and substrates with which some are actual protocols while others are not. Further studies categorised the physical quantum teleportation technologies, protocols, applicable infrastructures, implementation techniques and technologies. Information systems knowledge base was further studied in order to identify categories for standardization and creation of framework for security implementation.

4.4.5.2 Overview of the SecureQT-Framework Model

During the lessons learned based on DSR sub-cycles one to four, we used a circumscription and deductive reasoning guided by best practices to form the proposed SecureQT-Frameworks model as illustrated below.
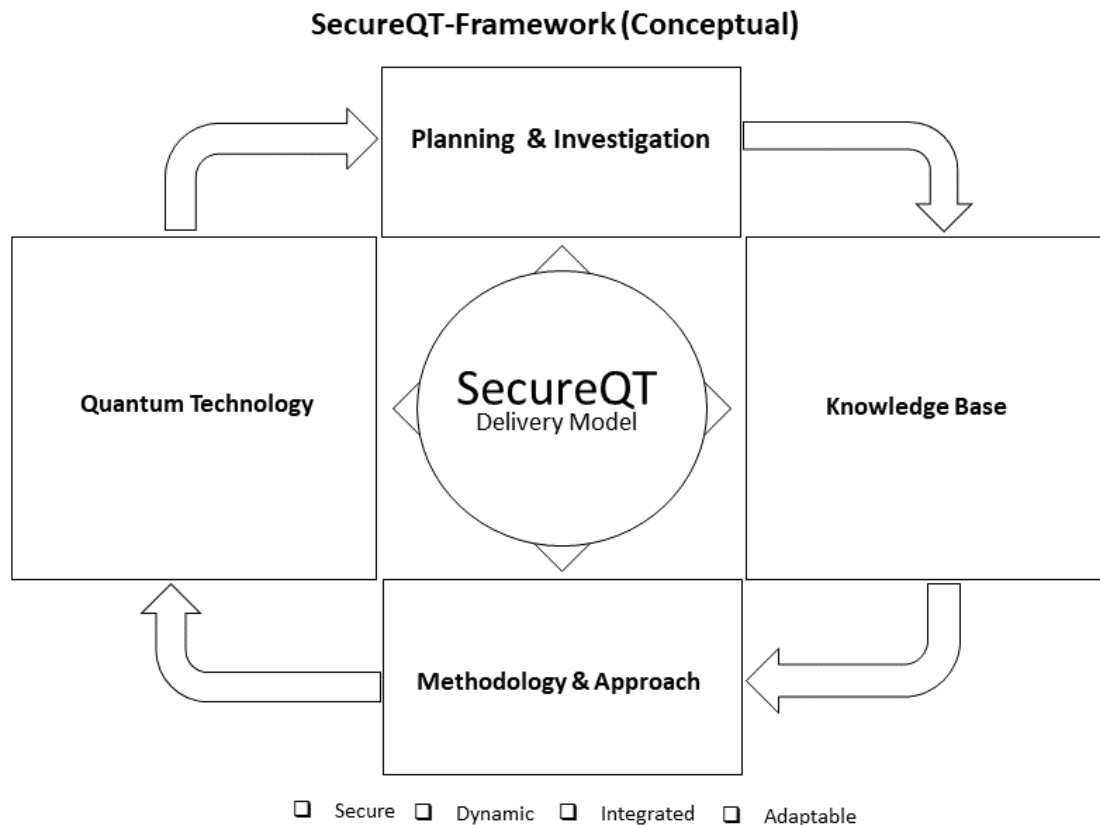
Figure 4.2: Conceptual SecureQT-Framework Model

The generic SecureQT-Frameworks in Figure 4.2 consists of five phases, namely:

- Phase A – Delivery Model

  This phase kick-starts the business case with requirements that outlines the need for implementing secure data transmission infrastructure based on quantum teleportation techniques. From the lessons learned in sub-cycles one to four and knowledge based we worked-out that such a generic framework should be driven by the security, dynamicity, integration and adaptability

requirements. Valuable input should be received from relevant stakeholders and ensure continuous support is provided throughout the phases. The delivery model contains a set of processes and procedures as well as tools that needs to be considered to embark on this journey. Infrastructures for quantum technology are a costly initiative, therefore full buy-in of the stakeholders and investment is needed.

- Phase B – Planning and Investigation

  The planning and investigation phase continues with the identification of the purpose, scope and goal of the SecureQT-Framework. Understanding the requirements and components needed for quantum teleportation supported by the four pillars of requirements in Phase A will lead into investigating and understanding the foundations of the knowledge needed by consulting the knowledge base. Extraction of key business goals should be made clear in order to ensure the framework process produces the required results. This may include processes that identifies or requires secure information exchange to realise their implementation, this approach further provides business with a technology-independent way of specifying objectives.

- Phase C – Knowledge Base

  Knowledge base is the phase that involves the multidisciplinary context of the SecureQT-Framework in which domain experts within their field are situated, this includes, but is not limited to Quantum Physics, Computer Science, Information and Communication Technology expertise. This is outlined in the primary suggestion phase that the QT knowledge is situated within multiple domains. The knowledge base further is the foundation for the infrastructure and connectivity sub-phase outlined in the literature review which includes:
  - Connectivity (Satellite, Fibre Optics, Freespace Optics, Microwave and Software Defined Networks).
  - Physical Infrastructures (Photonic Qubits, Nuclear Magnetic Resonance, Solid Sstate, Trapped Atoms, Atomic Ensembles, Optical Modes)

  Upon foundational knowledge and expert consultation a clear approach on the selection of infrastructure and connectivity mechanisms should be made with verification within the delivery model.

- Phase D – Methodology and Approach

Phase Ds methodology and approach as directed by the experts within the knowledge base should be able to outline the type of approach and methodology to use. This phase should also validate between delivery model and knowledge base for conformance to requirements, processes and components.

- Phase E – Quantum Technology

Phase E deals with the implementation of the quantum technology and the infrastructure guided by phase A and D. This is the core of the SecureQT-Framework infrastructure implementation. This phase implements the quantum technique which involves the QT variance and physical substrates and includes the QT protocols and methods. This phase continues with monitoring and maintenance.

4.4.5.3 Overview of the SecureQT-Framework Model with method
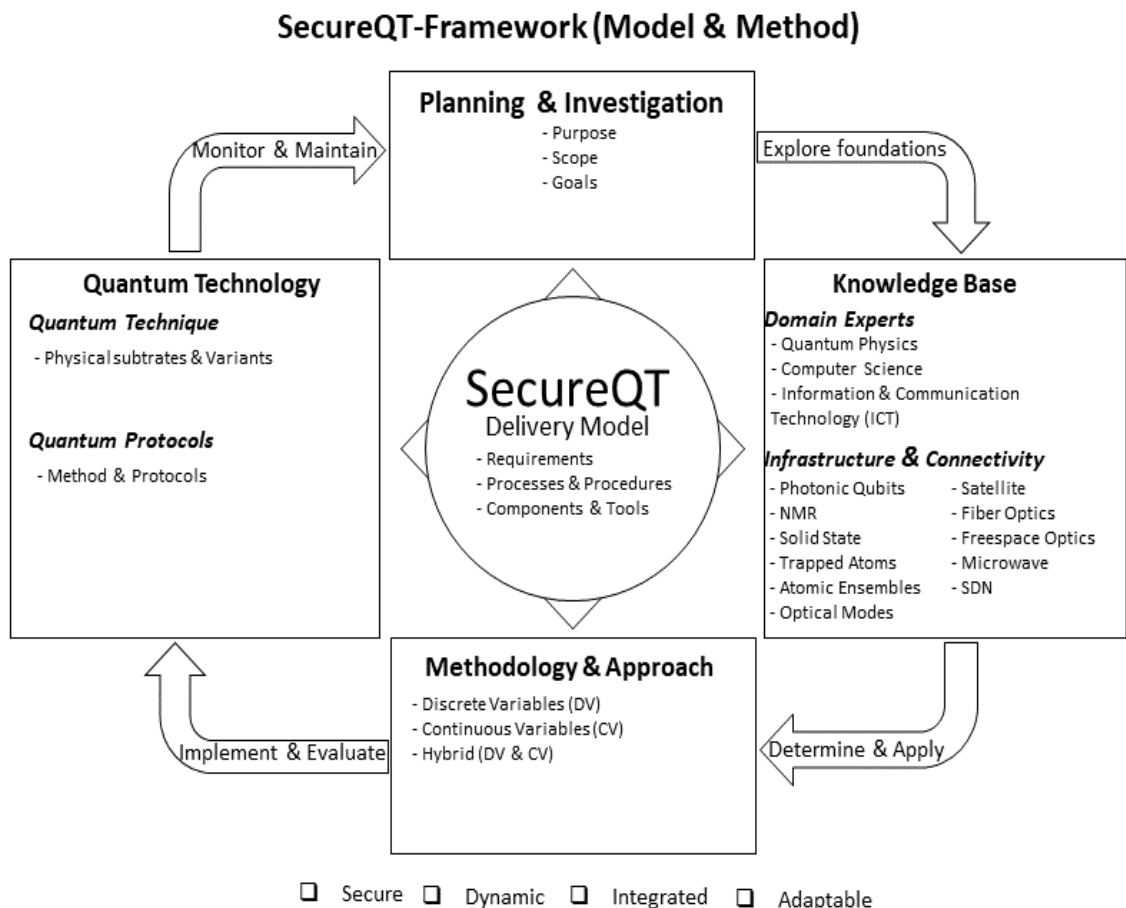
Figure 4.3: SecureQT-Framework (Model & Method)

Section 4.4.5.2 details the generic SecureQT-Framework model, this section with Figure 4.3 describes in detail the Frameworks Model and method that will be used to guide the implementation of secure quantum teleportation infrastructures. In addition to the Model this section outlines the:

- Planning and Investigation Phase which should ***explore the foundational knowledge*** within the knowledge base in which domain expertise and field expertise are found.
- The knowledge base which upon rigorous investigation within various expertise should be able to ***determine and apply*** the necessary infrastructure and connectivity needed.
- Methodology and approach which should be determined with the selection of preferred approach and specific methodology for ***implementation and evaluation.***
- The Quantum teleportation implementation and evaluation which should continue with the ***monitor and maintain*** process that will be further evaluated if it meets the goals as identified within phase B

4.5   Evaluation phase of the SecureQT-Framework

SecureQT-Framework evaluation occurred continuously within the design process. Significant number of micro-evaluations were carried out throughout each design decision. A thought experiment accompanied every decision where the design was mentally exercised by the researcher. Below we outline the formal evaluation that took place after the design artefact was stabilized.

As presented in section 3.4.3, and 3.6.3 the SecureQT-framework artefact was evaluated using a simulated experiment on various contexts described in detail within chapter 5, these included different operating environments that were modelled and stepped through to ensure the correctness of the experiment behaviour within its controlled environment. The contexts included basic quantum transmission of information from a sender to a receiver, transmission of information in the presence of an intruder all guided by hypothetical scenarios outlined as goals of the experiment. Informed arguments were used to ensure the artefact is grounded on empirical evidence. We further evaluated the artefact based on design objectives stated within this chapter section 4.3 as well as 3.7 using the assessment of artefact based on DSR as outlined by Hervner et al.

During the artefact evaluation several months have been taken in identifying relevant resources, modelling and unit testing of several tools and components as well as evaluating the information systems resources within the security and information transmission. Minor artefact redesign occurred during the conceptual phase in which three different phases were taken to finally have a stabilised conceptual design in consultation with the IS knowledge base. Information theory and computer science as

well as quantum physics literature played a major role in drawing up categories and classification schemes that were used while developing and evaluating the SecureQT-Framework. At the end of the SecureQT-Framework evaluation phase major simulated experiments were already completed with complex scenarios which were deemed as a success by the academic audience.

4.6   Conclusion phase of the SecureQT-Framework Development process

The conclusion phase of DSR process according to Vaishnavi and Kuechler (2015), contains various tasks, that involved presenting and reporting of the research results to selected audiences which are (academic or practitioner). This phase also used to reflect on lessons learnt and single-out contributions to the body of knowledge. Section 4 reflected on the research process by comparing SecureQT-Framework artefacts to approaches described in Section 3.2.4.

4.7   Conclusion

This chapter described the proposed generic SecureQT-Framework to guide the implementation of secure teleportation infrastructures in South Africa. A model and method was thus identified. The proposed framework was rigorously evaluated and contains features that are distinct to its self namely inherent security, dynamicity, integration and adaptability to the changing environment and technology landscape. The SecureQT-Framework fits exactly into what Purao (2002) defined as operational principles in which he emphasized artefacts which specify how things can be done in a reproducible manner. We have presented this model and method in the South African context, however it can be adopted by any other country or state that wishes to apply the framework.

CHAPTER FIVE
EVALUATION OF THE SECUREQT-FRAMEWORK

Simulated Experiment & Informed Argumentation Evaluating SecureQT-Framework

Chapter four detailed the design and build of the framework artefact. This chapter executes the design as well as the development of the experiment to empirically prove QT effects following the outlined SecureQT-framework.

5.1 Introduction

This chapter describes the plan that was applied in executing the methodological protocol outlined in chapter three (3). This experimental and development protocol enables reproducible results. It further allows the evaluation for its internal validity by the readers or the community at large that forms important criterion for selection when following a systematic review as outlined in chapter two of this study. In chapter two a gap was highlighted "protocols have been proposed however, their realisation is still a challenge. We thus said this argument introduces a need for simulating such protocols to evaluate their capability and realisation in practice," that is in-line with our research aim and objectives (RO1, RO2, and RO3) as well as our main research question RQ1.

This chapter therefore took a deductive cognitive process in order to present empirical evidence as the first step in the design and build of the SecureQT-Framework model and method which is the second step. The simulated experiment development ran parallel within the primary DSR cycle suggestion 1 and 2. Suggestion point one's goal was the development of an experiment to fulfil the hypothesis requirements, while suggestion point 2's goal was to design and develop the framework through the guidance of empirical evidence obtained from suggestion point 1.

This section is structured as follows:
a. Goals of the simulated experiment
b. Goal of the SecureQT model
c. Participants and
d. Material of the experiment
e. Tasks involved in the experiment as well as how they were executed
f. Deviation to the plan if any
g. Artefact evaluation (hypothesis measurement & empirical evidence).

The overall primary design cycle with four sub-cycles is outlined below in support of this chapter methodology and arguments. Figure 4.3 illustrate the high-level DSR process followed to achieve our objectives. The development phase describes the

experiment to simulate QT and also the development of the QT model for the SecureQT-Framework.

5.2   Goals of the Simulated Experiment

This section outlines the manipulation of the simulated experiment, the main goal is to fulfil the research main aim that said "The aim of this research is to investigate the effect of QT on the improvement of DC to DC communication security on the WAN for OSI Layer 2 technologies" supported by RO1 "To analyse the effect of using QT to securely transmit information" guided by RQ1 "How can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DCs?" The detailed goals of the simulated experiment are described in this section.

The following goals in the form of hypothetical scenarios were formulated:

1. **Goal 1**: Currently on DC-to-DC WAN on classical communication, an intruder can intercept/scan/monitor or listen in to information without either party on sender-A or Receiver-B noticing an intrusion has taken place.
2. **Goal 2**: When introducing QT techniques sender-A/receiver-B will detect the presence of an intruder, or be aware that an intruder has attempted to intercept/scan/monitor or listen in to the data while it is in transit.
3. **Goal 3**: In-case the intruder has managed to intercept the data, the intruder will not be able to make sense of the information.

In order to analyse the effects of QT to securely transmit data over the WAN, the researcher was faced with a deep learning curve employing foundations within the knowledge base (information theory, computer science and aspects of quantum physics) to build a case for the simulated experiment guided by a SLR.

A conceptual framework of QT simulation amenable to mathematical analysis and simulation was presented in Figure 5.1. This involved synthesis of key insights and desperate knowledge. According to (Shanks et al., 1993) "*conceptual studies can be effective in building new frameworks and insights and can be used in a current situation or to review existing bodies of knowledge. Its strengths are that it provides a critical analysis of the situation which can lead to new insights, the development of theories and a deeper understanding*".
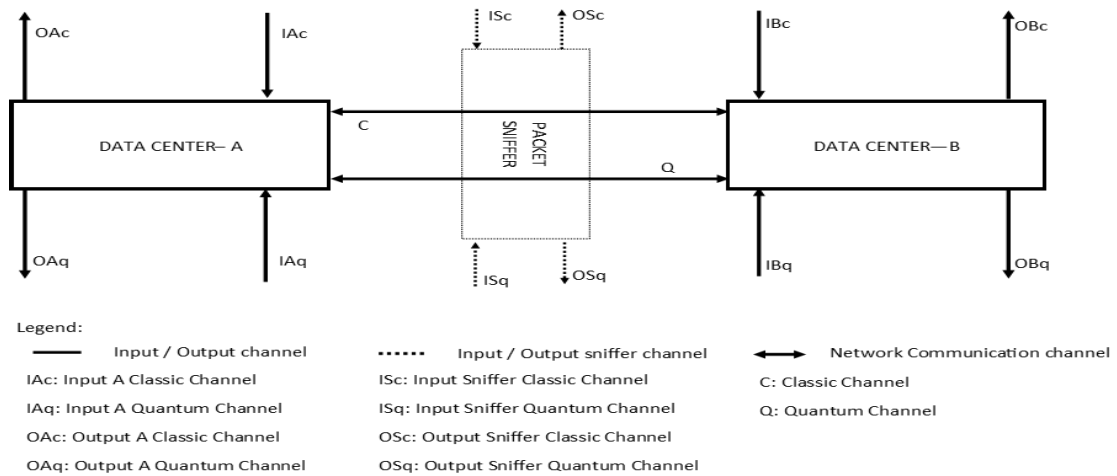
Figure 5.1: SecureQT-Framework Conceptual

The simulated experiment executes artefact using artificial information, and involves the use of *hypothetical scenarios* to get around the issue of real-world access to application while still providing convincing evidence and be able to assemble detailed scenarios around the artefact to demonstrate its usefulness. The process is outlined within Figure 5.2. Using Scenarios was a good path to pursue, as a forced scenario which allows the artefact not to rely on indefensible generalization in a specific context.
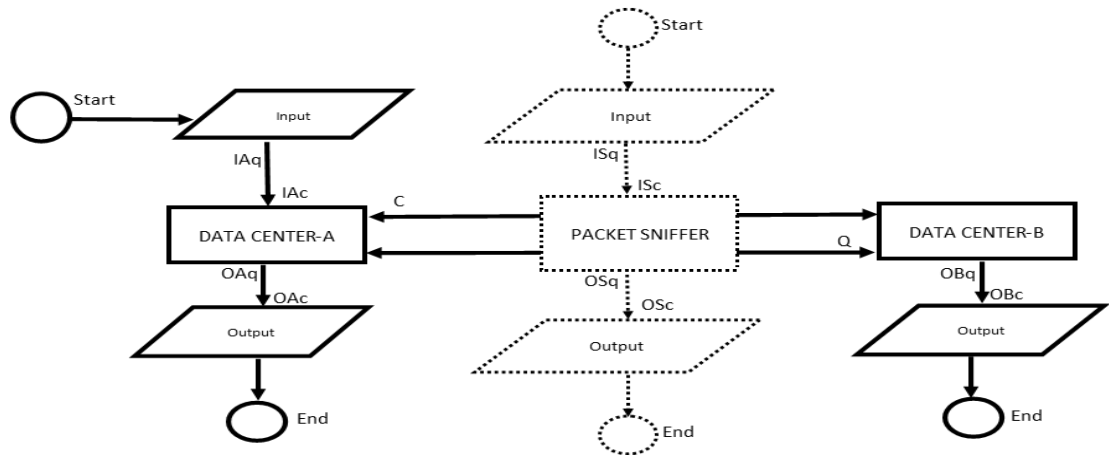
Figure 5.2: SecureQT-Framework Evaluation Process

The goal scenarios are further broken-down and detailed in sections below.

5.2.1 Goal 1

To realise this goal we configured a packet sniffer (in monitor mode or promiscuous mode) between the communicating hosts through access point or switch. Layer 2 data frame headers were captured and analysed using Mininet and Wireshark. The below steps were followed:

a. Installation and configuration of Mininet and Mininet-WiFi on a VM with Wireshark.

b. Create topology using Python API Scripts.

c. Start Wireshark from command line or GUI to capture data frames.

d. Run the simulation scripts to create traffic between the hosts.

e. Stop Wireshark and save the file for analysis and reporting.

5.2.2 Goal 2

To realise this goal SQUANCH was used to simulate the quantum transmission based on Quantum Teleportation and its inverse Superdense Coding in order to capture multiple scenarios related to the intruder. These included the introduction of a third party to assist with the transmission of information on classical and quantum channels.

The process below was followed:

a. Install and configure SQUANCH

b. Simulate quantum teleportation transmission between two hosts acting as data centres

c. Start Wireshark to intercept the transmission messages (local host based simulation)

d. Stop Wireshark and save the file for analysis and reporting

e. Use Python visualization tools to display teleportation fidelity and qubit transmission

5.2.3 Goal 3

This goal is also covered with goal 2 though this goal was more specific to observe the data an intruder will get to prove quantum teleportation relevance/effect in detection of an intruder.

The following protocol was followed:

a. Ensure SQUANCH is already installed

b. Simulate quantum teleportation transmission between two hosts A and B with assistance from host C acting as data centres and C as a controller

c. Simulate an intruder to sniff/intercept the data during transmission as host E

d. Use Python visualization tools to display teleportation fidelity and qubit transmission

5.3 Goals of the SecureQT Model

This section's goal is to design and develop a generic secure quantum teleportation framework that will be used to guide the implement layer 2 data transmission infrastructure in South Africa in order to minimize threats of network tapping, monitoring and eavesdropping on the wire. The generic framework must be abstract in nature and allows for adaptability, integration, dynamicity and be inherently secure with a model

and method to guide its implementation. The main participant in this section is the researcher conducting literature reviews in order to construct such a framework guided by the empirical evidence within the simulated experiment.

5.4 Participants and material of the Experiment

This section with Figure 5.3 outlines the participants involved in the simulated experiment.
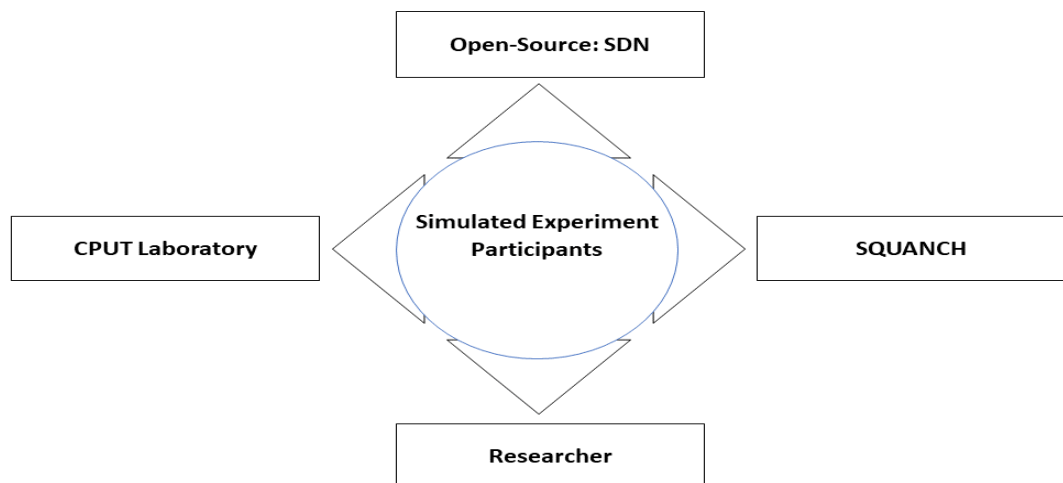
Figure 5.3: Simulated experiment participants

5.4.1 CPUT Laboratory

The university supplied the resources to carry out the research and the simulation of the experiment including the availability of the CPUT laboratory to access all necessary resources e.g. Internet, server/laptops/desktops.

5.4.2 Researcher

The researcher utilised the resources afforded by the university within the laboratory to carry out the study as well as conducting the experiment that forms the basis to propose the SecureQT-Framework.

5.4.3 Open Source SDN

The Open-source community has the tools and components with which the experiment was conducted. The outcomes of the experiment will then be contributed back to the community to allow review, validation and further work to be contributed to drive the knowledge forward. The Software defined networks (SDN) tools and related packages were cloned/downloaded from GIT Hub to enable the realisation of the experiment. Software that could not be found from Git hub were downloaded from their respective sources.

5.4.4 SQUANCH

SQUANCH (Simulator for Quantum Networks and Channels) is an open-source Python framework for creating performant and parallelized simulations of distributed quantum information processing (Bartlett, 2018b). This tool was selected after careful investigation and consideration from various tools and it was found to be the necessary tool fitting my purpose.

5.5   Simulated Experiment Material (Tools & Components)

This sub-section describes materials and components involved within the experiment setup.

a. HP Intel i5 8th Generation with built-in 4GB RAM, extended 16GB RAM, 500GB HDD, Windows 10 Operating System (OS). External 2TB HDD to ease the space usage for QT experiment and Wireshark storage requirements.

b. Open-Source Software defined Networks tools and Components (Infrastructure) used:

1. Oracle VirtualBox was used as a high performance and Open Source virtualization product.

2. Ubuntu OS used within our virtualization as an Open Source Linux distribution based on Debian.

3. OpenFlow communications protocol allowing access via forwarding plane of a network's switch/router on the network.

4. Mininet utilised to create a virtual network, executing real kernel, switches and application code.

5. Mininet-WiFi used to work with Wireless SDN and using both WiFi Stations and Access Points

6. Wireshark used as a packet sniffer and for deep packet inspection and for localhost to localhost capture and analysed through Wireshark.

7. SQUANCH was used for simulating quantum networks specially quantum secure transmission.

5.6   Simulated Experiment Activities

This section with Figure 5.4 outlines activities performed during the experiment design and development. This will allow replication of the experiment and results with minimum consultation to the researcher. These activities are guided by the DSR sub-cycles suggestion and development phases and they all within the conceptual framework as outlined.
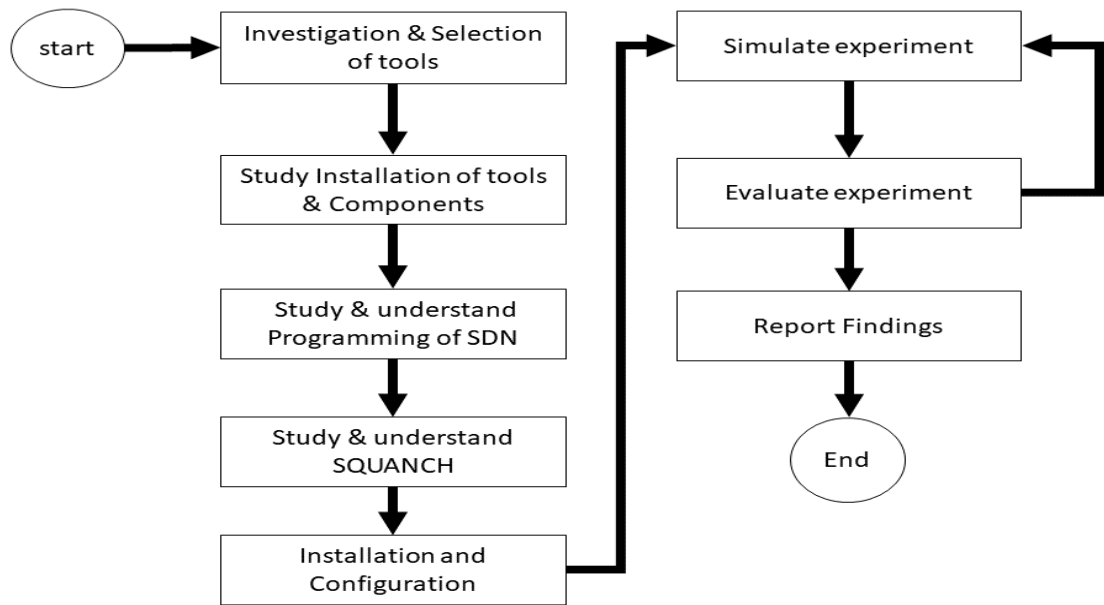
Figure 5.4: Simulated Experiment Activities

5.6.1 Investigation and Selection of Tools & Components

This activity was guided by Primary DSR cycle suggestion and development, further supported by DSR sub-cycles 1 and 2s problem awareness. The knowledge base is replete with tools and components forming the basis for an intense investigation to determine the best products and components that fit our purposes. After an intense investigation for relevant tools, we thus selected as outlined in section 5.4.

5.6.2 Study Installation of Tools and Components

Upon the completion of the tools selection a series of studies on the installation process on a trial and error-basis was conducted until a suitable method of installation was found that formed the basis of the installation used for this experiment. The tools and components on section 5.4 were part of this study in its entirety. Several months to a year was invested in the analysis of the tools that will allow us to prove or disprove the quantum teleportation theoretical basis as described in chapter 2 and chapter 3. Major trial and error stages were performed in the installations, setup and configuration of the various tools that were part of the investigation with potential to be used as simulation resources for our purposes. After a rigorous comparison of the tools we were able to successfully determine the correct tools for our evaluation as presented in section 5.4.

5.6.3 Study and Understand Programming of SDN

The one area that consumed more-time was the study to understand the SDN tools and their programming. Multiple SDN components exist, however OpenFlow (OF) with Mininet and Mininet-WiFi were finally selected and studied that introduced another awareness cycle. Wireshark was selected as the Open Source Packet sniffers with a

less intensive learning curve. We standardised the reporting to be in Python as one of the tool sets selected for this overall experiment simulation, analysis and reporting. Mininet was studied together with the possible applicability of plugins like OF and its extension of Mininet-WiFi library which presented a good case for its selection and understanding of the nature of its programmability.

5.6.4 Study and Understand SQUANCH

SQUANCH "is designed specifically for simulating quantum networks, acting as a sort of quantum playground to test ideas in quantum transmission and networking protocols" (Bartlett, 2018a). This tool was selected with a good standardization on Python that is familiar to the researcher and required less intensive investment in understanding the background of the language. This allowed the researcher to interact directly with the product to execute mini-simulations before engaging in the actual simulation for this study. The tool introduced a great learning curve to simulate intruders and exceptions within the transmission medium. Few components and tools such as freespace optics path loss were added by the researcher in the core of the SQUANCH code, the Python math library was also integrated to add the Python use-case for simulating the freespace optics attenuation algorithm.

5.6.5 Installation and Configuration

The installation and configuration was a seamless process, only few incompatibilities were found within the Operating System versions. However, after multiple trial and errors it was fixed allowing the creation of a standard way of installing and configuring the tools. Cloning from Git Hub had to be done by first ensuring the type of OS and package dependencies already exists.

Installations were as follows:
1. Installation of Oracle VirtualBox.
2. Installation of two UbuntuVMs for OpenFlow with Mininet, Mininet-Wifi and Wireshark.
3. Installation of SQUANCH on Ubuntu VM.
4. Installation of Python modules and packages.
5. Configuration of the Linux Ubuntu Virtual Machines.
6. Configuration of OpenFlow, Mininet Topology, Wireshark and Mininet-Wifi.
7. Upgrade and update of the OS packages for development.

The virtual machines were installed based on the below configuration:

5.6.5.1   Mininet-Wifi VM specification (Wireshark, Mininet & OpenFlow)

- Operating System: Ubuntu 64bit

- Memory: 6GB

- CPU: 3

- Extras: GuestOS, NAT and HostOnly network adapter

5.6.5.2   SQUANCH VM Specification

- Operating System: Ubuntu 64bit

- Memory: 8GB

- CPU: 4

- Extras: GuestOS, NAT and HostOnly network adapter

5.6.6 Simulation of Experiment

The experiment was finally simulated with the relevant tools and packages. Hypothesis were tested and re-verified against literature and other experimental findings to ensure we conform to the standard reported findings within literature experiments and theoretical findings.

Protocol for the simulation

5.6.6.1   Goal 1 - Protocol

1. Station 1 sends a message to Station 2.
2. Intruder intercept/monitor the exchange of information between Station1 and Station2.
3. Intruder gains access between the communicating stations
4. Station 1 and Station 2 are not aware that an intruder tapped into their communication and got access.

5.6.6.2   Goal 2 – Protocol guided by section 2.2.2

It is argued that generally all QT experiments have the same underlying building blocks. Two distant parties, Host A and Host B, are connected via a classical information channel which shares maximal entangled state. Host A has an unknown state $|\psi\rangle$ which needs to be sent to Host B. Host A performs a joint projective measurement of its own state and other half of the correlated state and communicates the outcomes to Host B, that operates on its own half of the entangled state accordingly to reconstruct $|\psi\rangle$.

The protocol then goes as follows:

1. Host A generates two entangled state particles $|AB\rangle=1/\sqrt{2}(|00\rangle+|11\rangle)$ while half of the state is kept and the other half is sent to Host B

2. Host A entangles own qubit $|\psi\rangle$ with own ancilla A by applying controlled-not (CNOT) and Hadamard (H) gate operators

3. Host A jointly measures $|\psi\rangle$ and A, and communicates the outcomes to Host B through a classical channel. Host B's qubit is now in one of four possible Bell states, one of which is $|\psi\rangle$, and he will use Host A's two bits to recover $|\psi\rangle$

4. Host B applies a Pauli-X gate operator to own qubit if Host A's ancilla collapsed to $|A\rangle \mapsto |1\rangle$, and applies a Pauli-Z operator to own qubit if qubit collapsed to $|\psi\rangle \mapsto |1\rangle$. Thus Host B transformed $|B\rangle \mapsto |\psi\rangle$.

5.6.6.3   Goal 3 – protocol guided by QT Inverse: Superdense Coding

To realise this goal we need to empirically demonstrate how quantum networks can be resistant to intruders ("man-in-the-middle") attacks by using QT inverse called Superdense coding which modifies the protocol of Superdense coding to archive the results. Host C as the manager/controller will distribute Bell pairs to Host A and Host B, and Host A will attempt to send a classical message to Host B. However, a fourth party, called Host E as an intruder, will try to naively intercept the message Host A is sending to Host B. Host E will then measure each qubit from Host A, record the results, and re-transmit the qubit to Host B.

This protocol goes as follows:

1. Host C generates EPR pairs in the state $|AB\rangle = 1/\sqrt{2}(|00\rangle + |11\rangle)$ sending one particle to Host A and another to Host B

2. Host A encodes its own two bits of classical information in the relative sign and phase of its own qubit by acting with the Pauli-X and Pauli-Z gates. Formally, if Host A has two bits, b1 and b2, Host A applies X if b2=1 and then applies Z if b1=1. Host A then sends the modified qubit to Host B, but gets intercepted by Host E before reaching Host B.

3. Host E wants to know Host A's message, then Host E naively measures each qubit intercepted from A and records the result. Host E then sends the qubits to Host B, hoping B won't realise the intrusion.

4. Host B receives the qubit from Host E (who B thinks is Host A). Host B disentangles the Pauli-X and Pauli-Z gates components of the qubit by applying CNOT gate and H gate to Host A's qubit and Host C's qubit. Then Host B measures each of A's and C's qubits to obtain b1 and b2, respectively.

5.6.7 Evaluation of Experiment

The simulated experiment was evaluated based on hypothetical scenarios and empirical evidence as described in the goals section.

5.6.8 Report Findings

The findings are reported using tables, charts and images to ease the understanding of the data collected within the simulated artificial data. This is described in detail on section 5.8.

5.7 Deviation from Plan

Initial plan of the experiment during the proposal stage was to use databases and R tools for recording and reporting the results. However, after standardizing the toolsets into Python programming to realise the project on a common language specification, we have decided to alternatively utilise already existing python packages that allows us to record, analyse and report results without using any extra toolsets like databases or visualization as python can handle, thereby limiting the scope to an integrated environment standardized within python packages.

5.8 Evaluation

The review of the literature included a study of a proposed methodology appropriate for addressing the problem situation. In order to evaluate our work we based it on the design evaluation in which the artefact is assessed by building scenarios with artificial information and decision processes with intensive statistical analysis on outcomes. The experimental analysis was performed as a controlled experiment, in which the artefact is tested in a stable laboratory environment by simulating the artefact's function using artificial information. A descriptive evaluation was also made through informed arguments, where existing information was utilised to construct a convincing opinion on the usefulness of the artefact and through the building of scenarios around the artefact to demonstrate its usefulness covering goal 1, goal 2 and goal 3 as described in the sections below.

5.8.1 Simulation Mininet-WiFi (Goal 1)
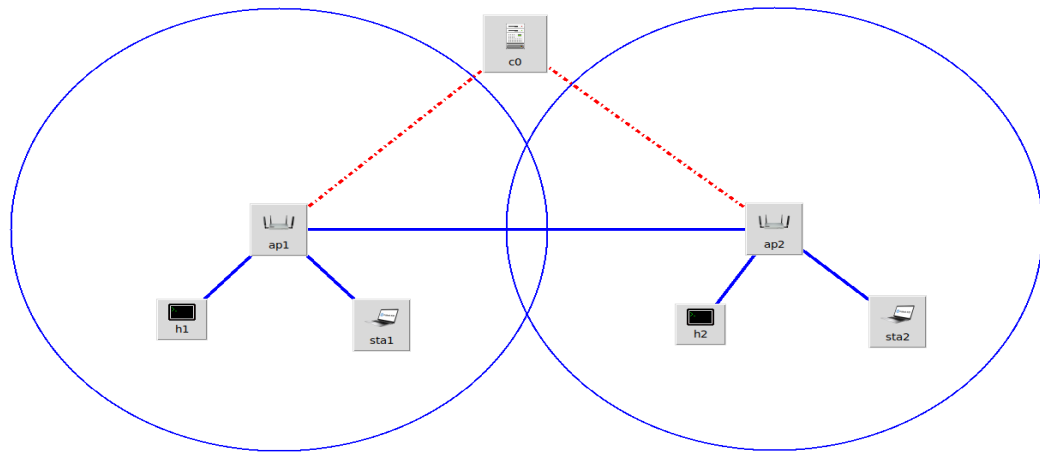
Figure 5.5: Mininet-Wifi Design Experiment

To realise Goal 1 a Mininet-wifi wireless network emulator was utilised as a fundamental to evaluate, test and prototype end-to-end network architectures and applications. Mininet-Wifi is the extension from Mininet Software defined Network (Fontes et al., 2015). It adds virtualised Wifi access points (APs) and Wifi Stations (STAs) all supporting IEEEs 802.11 family of drivers and protocols. OpenFlow SDN is integrated within the Mininet-wifi to support bi-casting over 802.11 access points and integration with physical NICs supporting mobility. Mininet-Wifi emulates wireless channels, setting link parameters i.e. packet loss, delays etc. The results from this emulation are described below:

5.8.1.1 Goal 1 – Protocol Results – Prove an Intruder can Sniff Packets not detected

The below code in figure 5.6 was used to produce the design experiment using Python API run through the Mininet-Wifi CLI.

Figure 1.6 Mininet API code

The image above outlines how the setup was done. Wireshark was installed to sniff the traffic between the communicating stations sta1 and sta2. In order to find the sniffed packets Wireshark was configured to run on both loopback: lo and hwsim0 interfaces as outlined below on figure 5.7.
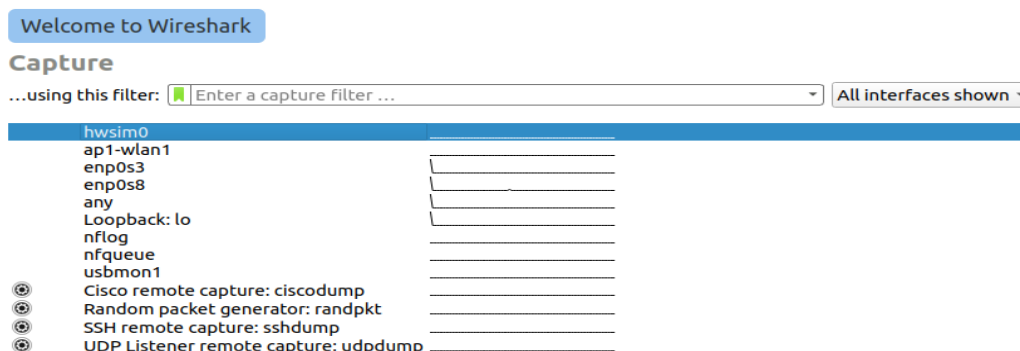
Figure 5.7 Wireshark Packet Sniffer

A filter was set to run on hwsim0 and later to loopback: lo to capture all traffic and communication between sta1 and sta2. A controller c0 was used to direct the communication between ap1 and ap2.

The results were captured as follows:
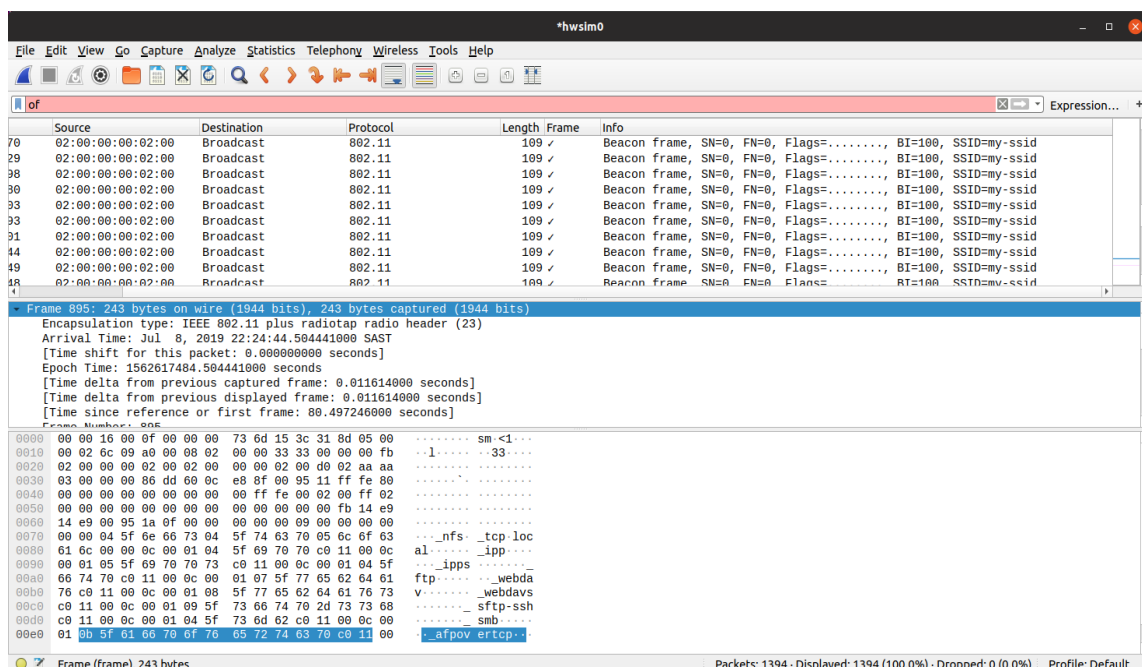
Figure 5.8 Wireshark 802.11 broadcast

Wireless traffic on 802.11 interfaces was captured. The WLAN frames have four address fields in their headers, used to identify the sender of the Ethernet frame,

receiver of the frame and the extra two used to transparently send packets over wireless distribution system that gets encapsulated into 802.11 WLAN frame as the sender of the WLAN frame and receiver of the frame. These frame formats are used as frame addressing mechanisms. The loopback openFlow messages presented on Figure 5.9.
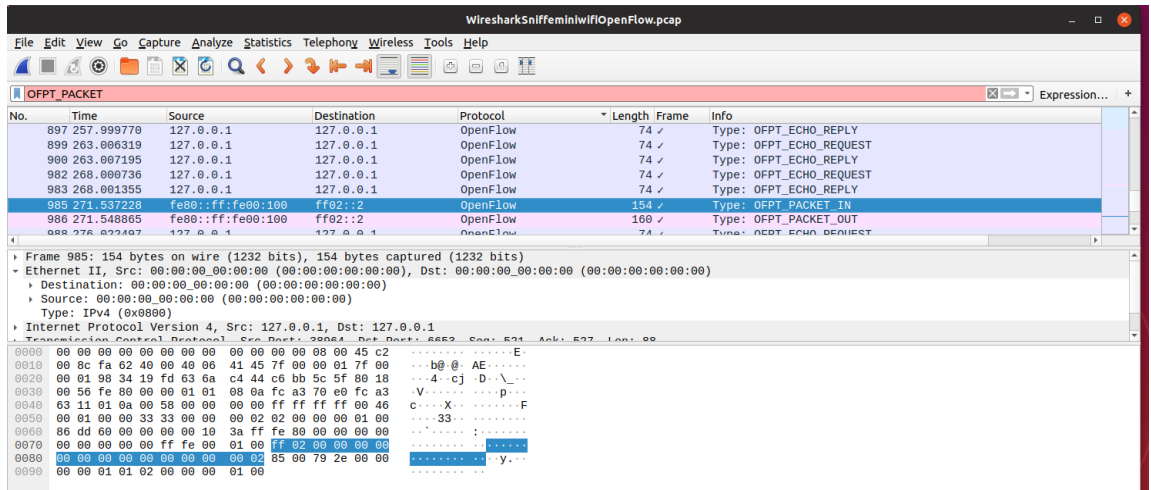
Figure 5.9 OpenFlow reading Packets

The image above outlines the results of the frame through openFlow data frames captured. We were able to observe the request and response between the hosts as well as noticing their acknowledgements and passing on of information. Our sniffer was setup on promiscuous/monitoring mode.

5.8.2 Simulation of Experiment Quantum Teleportation (Goal 2)

To realise Goal 2 the experiment was evaluated based on a number of scenarios which included the ability to generate and distribute quantum bits on the SQUANCH framework. As outlined in Goal 2 protocol, the following Figure 5.10 circuit was used.
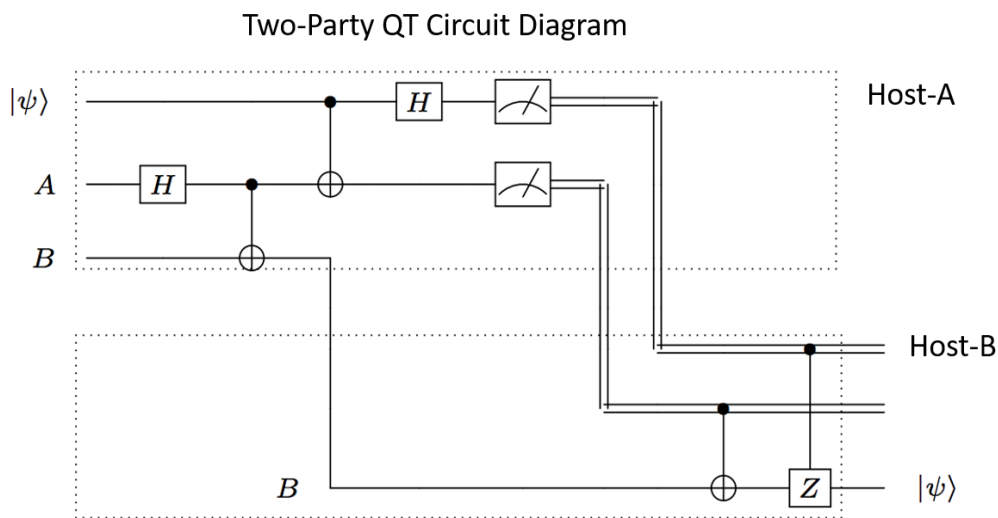
Figure 5.10 Two-Part QT Circuit

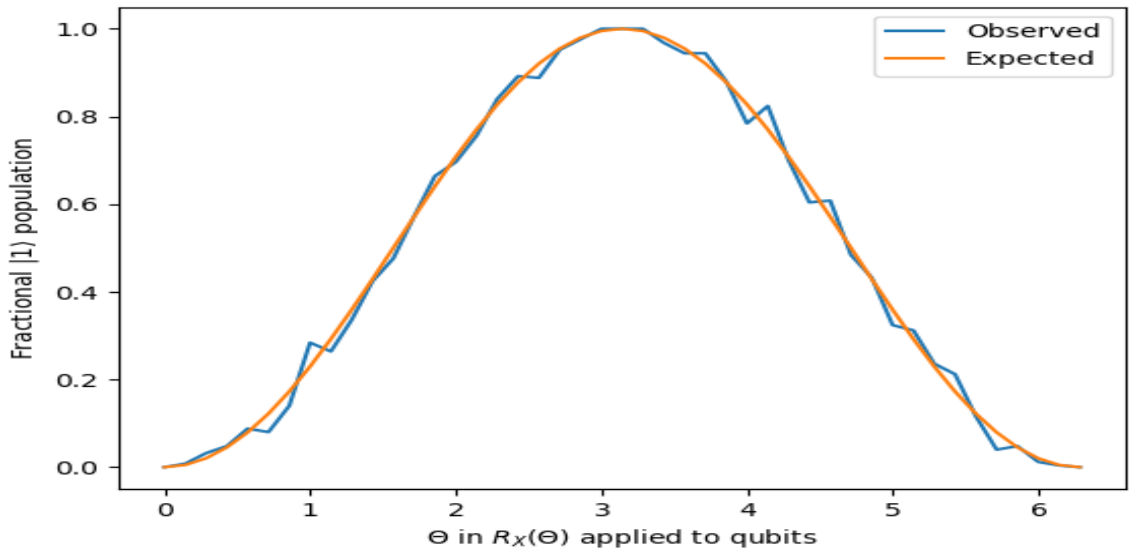## 5.8.2.1 Goal 2 – Protocol Results 1- Classic and Quantum Channel String Text

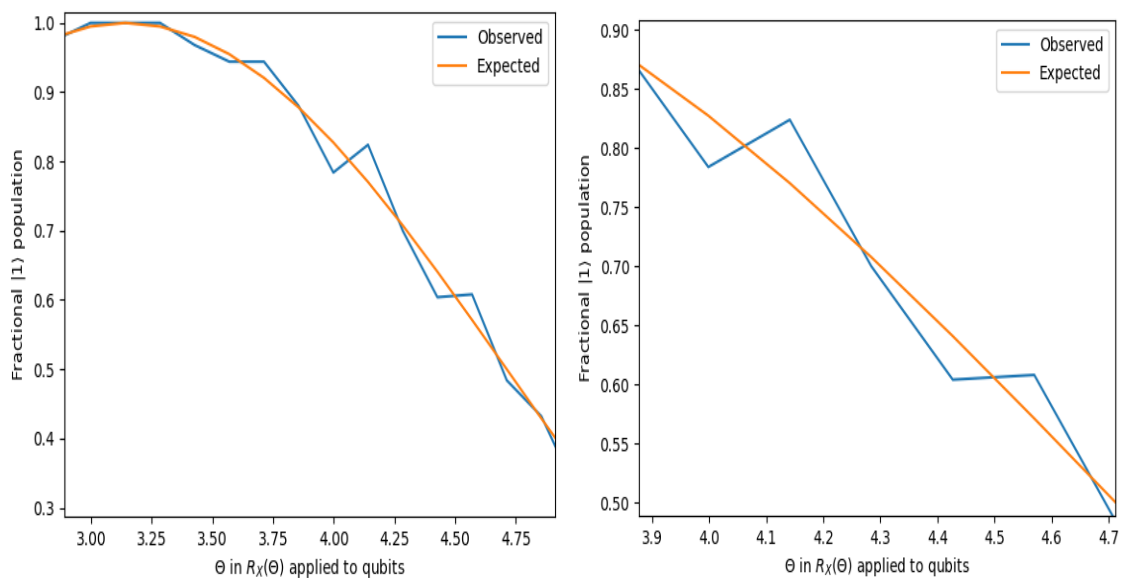**Figure 5.11 String text Teleportation**

Figure 5.12 String teleport Qubit values

The Figure 5.11 and 5.12 outlines the teleportation of an ensemble of identical states $RX(\theta)|0\rangle$ on values of θ. We measured each teleported state in order to observe how it compares with the expected outcomes. The following snippet outlines the instructions applied.

```
angles = np.linspace(0, 2 * np.pi, 45)  # RX angles to apply
num_trials = 250                # number of trials for each angle
# Prepare the initial states in the stream
qstream = QStream(3, len(angles) * num_trials)
for angle in angles:
    for _ in range(num_trials):
        q, _, _ = qstream.next().qubits
        RX(q, angle)
```

5.8.2.2 Goal 2 – Protocol Results 2 – Classic and Quantum Channel Message

Figure 5.13: SecureQT-StringTeleport Results

In order to realise goal 2 second scenario was to test the state teleportation of an actual message from Host A to Host B, the states were broken down into classical message bits then teleported. We then observed the arrival and the message teleported.

5.8.2.3 Goal 2 – Protocol Results 3 – Classic and Quantum Channel using an Image

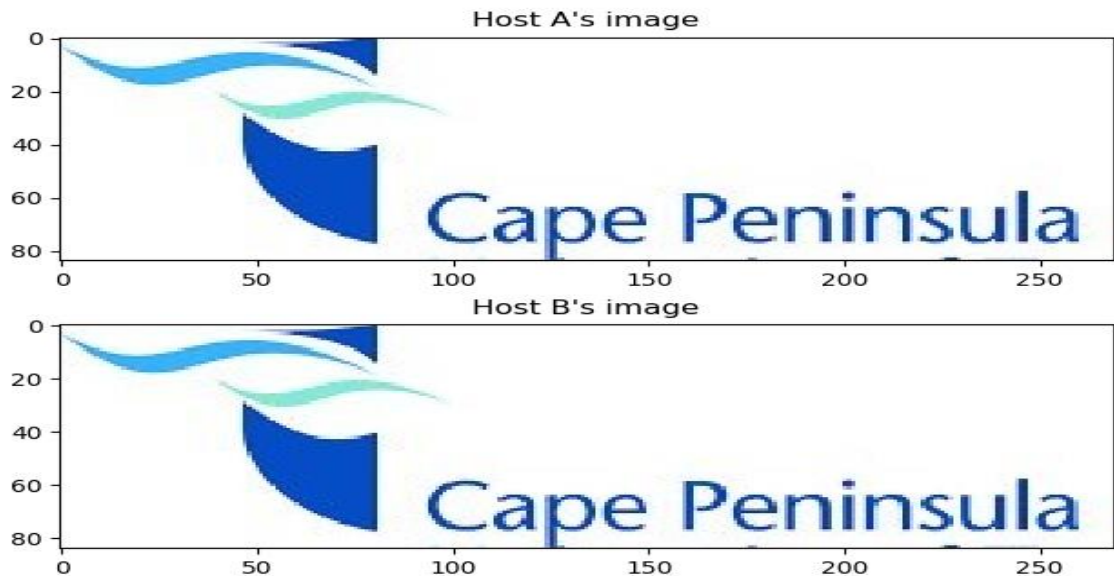**Figure 5.14 Classic & Quantum Teleport**

The last scenario to achieving goal 3 was to take an image logo from the university website, remove the metadata to make the image smaller to avoid the long running of the experiment. We then executed the simulator that runs for an hour to reproduce the exact state from Host A to Host B. This was done without an intruder. The instructions were executed as follows:
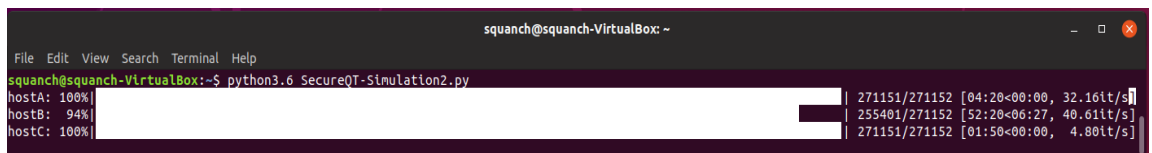
Figure 5.15 Teleport Simulation Progress

The circuit for this simulation is similar to goal 3's circuit, but without the presence of an intruder. We observed the distribution quantity of quantum states tracking time of arrival. The following snippet was used:

```
#https://realpython.com/python-matplotlib-guide/
#https://matplotlib.org/3.1.0/gallery/subplots_axes_and_figures/subplots_demo.html
def plot_images(hostb_bits):
    hostb_img = np.reshape(np.packbits(hostb_bits), img.shape)
    #f, ax = plt.subplots(1, 2, figsize = (18, 9))
    f, ax = plt.subplots(2)
    ax[0].imshow(img)
    ax[0].axis('on')
    ax[0].title.set_text("Host A's image")
    ax[1].imshow(hostb_img)
    ax[1].axis('on')
    ax[1].title.set_text("Host B's image")
    print("\nComplete Simulation Results")
    plt.tight_layout()
    plt.show()


# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())
```

5.8.3   Simulation of Experiment Quantum Teleportation (Goal 3)

The experiment was evaluated based on a number of scenarios, initially the researcher experienced hurdles on the images, the SQUANCH framework standardised their image recognition to byte signed, which means we could only use (.jpg and .bmp) that could be broken down into smaller chunks of bit stream two dimensional array. The images however gave further problems when trying to flatten them instead of just unpacking e.g. snippet

```
bitstream = list(np.unpackbits(img)) vs bitstream = list(img.flatten())
```

Metadata of the images had an impact on the size of the images that caused the simulator to run for a very long time compared to saving images without metadata. The researcher had to increase the number of CPUs to 3 and RAM to 8GB on the VM to ensure a minimised runtime and timely response. After this addition the maximum runtime was reduced to under one hour. The image below describes the circuit diagram of the results as outlined in sub section 5.6.6.3
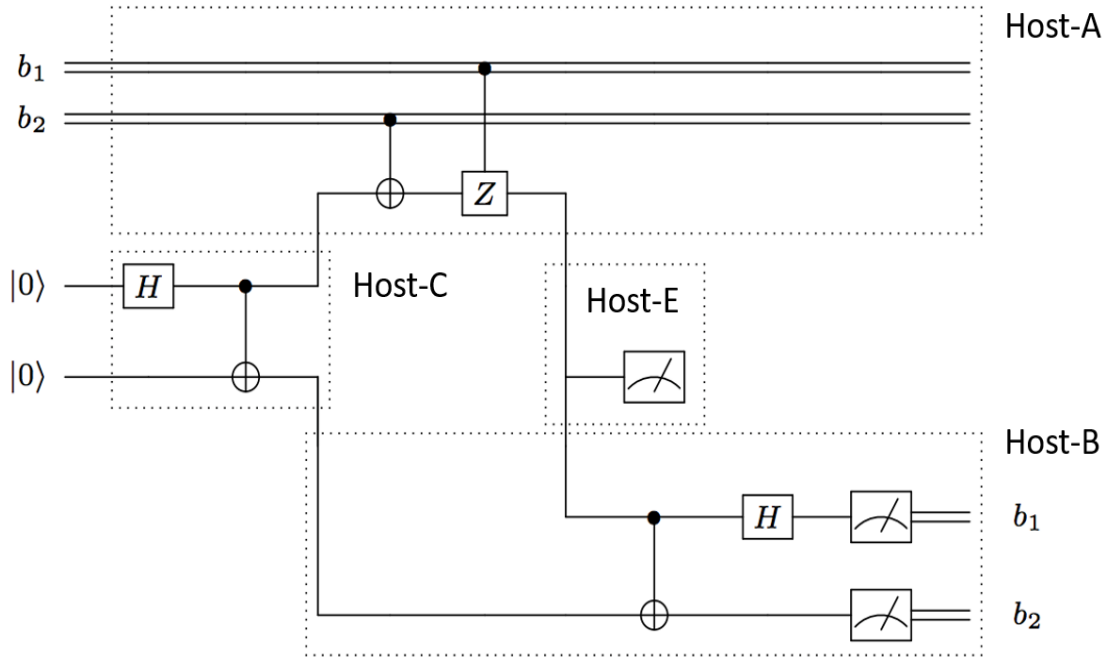
Figure 5.16: Four-Party QT Circuit Diagram

5.8.3.1 Goal 3 – Protocol Results 1 Classic and Quantum Channel with Intruder

We used a dense image logo from CPUT as our initial run monitoring the progress. The results are presented on Figure 5.17 as below:

Figure 5.17 Horiz & progress QT

We observed that when applying quantum teleportation protocol where there is an intruder trying to monitor or listen in on the communication, the intruder only got random noise which will not attribute to anything useful. We also observed the destination host B whose state is somehow compromised revealing the presence of an intruder. The snippet was as follows:

```
# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())
print("Bitstream {}".format(len(bitstream)))

# Prepare an appropriately sized quantum stream
qstream = QStream(2, int(len(bitstream) / 2))
out = Agent.shared_output()
# Instantiate agents
```

```
hosta = hostA(qstream, out, data=bitstream)
hostb = hostB(qstream, out)
hostc = hostC(qstream, out)
hoste = hostE(qstream, out)
# Connect the agents to form the network
hosta.qconnect(hostb)
hosta.qconnect(hoste)
hosta.qconnect(hostc)
hostb.qconnect(hostc)
hostb.qconnect(hoste)
# Set photon transmission rate
hosta.pulse_length = 1e-9
hostb.pulse_length = 1e-9
hoste.pulse_length = 1e-9
hostc.pulse_length = 1e-9
# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()
# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

5.8.3.2 Goal 3 – Protocol Results 2 Classic and Quantum Channel Less dense Image
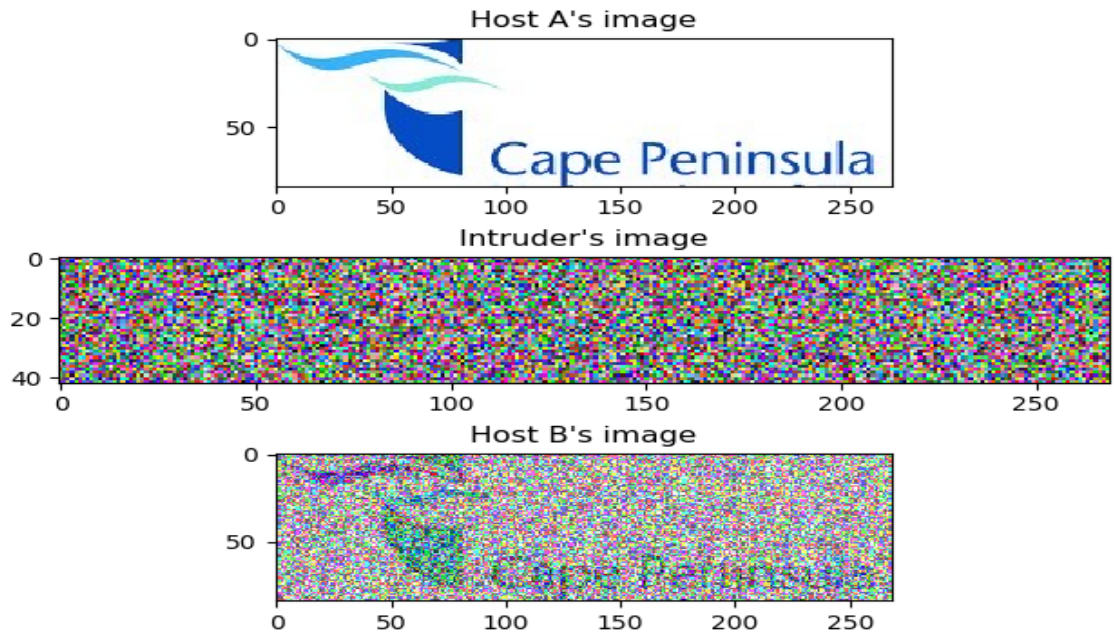
Figure 5.18 QT with Intruder

Results from the second scenario of goal 3 was setup without any freespace channel between sender A and receiver B. Controller C was used to distribute the classical bits situated between the sender and receiver. An intruder was also situated between the sender and receiver. The receiver's image though showed elements of compromise, the results were a little clearer compared to result 1 though lots of noise was surrounding the image revealing the presence of an eavesdropper.

5.8.3.3 Goal 3 – Protocol Results 3 – FiberOptic Quantum Channel 1KM
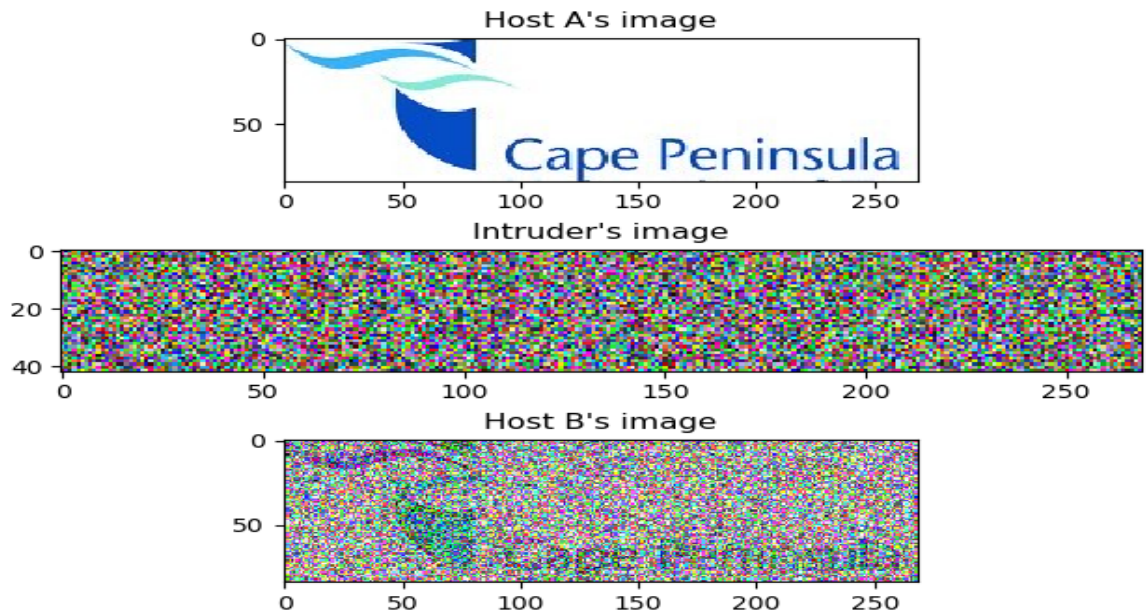
Figure 5.19: 1KM Fibre Optic QT Channel

Results from the third scenario of goal 3 was setup on a fibre channel with a distance of 1km between sender A and receiver B. Controller C was situated at half the distance 0.5km from both the sender and receiver. An intruder was also situated 0.5km between the sender and receiver. The fibre has an attenuation error rate. Compared to result 1, goal 3 evaluated that the intruder also got random noise from the interception, however though the receiver's image showed elements of compromise, the results were a little clearer compared to result 1, though lots of noise was surrounding the image revealing the presence of an eavesdropper along the fibre.

The snippet was as below:

```
# Connect the agents over simulated fiber optic lines
hosta.qconnect(hostb, FiberOpticQChannel, length=1.0)
hosta.qconnect(hoste, FiberOpticQChannel, length=0.5)
hosta.qconnect(hostc, FiberOpticQChannel, length=0.5)
hostb.qconnect(hostc, FiberOpticQChannel, length=0.5)
hostb.qconnect(hoste, FiberOpticQChannel, length=0.5)

# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()

# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

5.8.3.4 Goal 3 – Protocol Results 4 – FiberOptic Quantum Channel 5KM
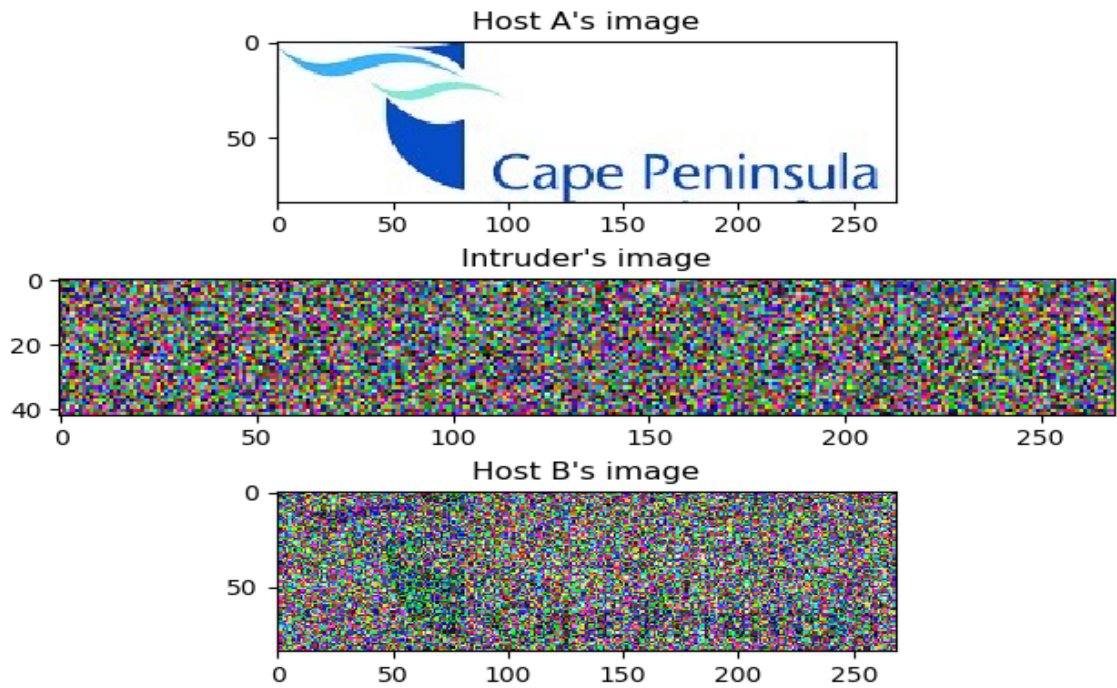
Figure 5.20: 5KM fibre Optic Channel with Attenuation

Results from the fourth scenario of goal 3 was setup on a fibre channel with a distance of 5km between sender A and receiver B. Controller C was situated at half the distance 2.5km from both the sender and receiver. An intruder was also situated 2.5km between the sender and receiver. The fibre has an attenuation error rate. Compared to result 3, goal 3 evaluated the intruder also got random noise from the interception, however the receiver's image showed a compromise, the results were more dense compared to result 3.

The snippet was as below:

```
# Connect the agents over simulated fiber optic lines
hosta.qconnect(hostb, FiberOpticQChannel, length=5.0)
hosta.qconnect(hoste, FiberOpticQChannel, length=2.5)
hosta.qconnect(hostc, FiberOpticQChannel, length=2.5)
hostb.qconnect(hostc, FiberOpticQChannel, length=2.5)
hostb.qconnect(hoste, FiberOpticQChannel, length=2.5)
# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()
# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

5.8.3.5 Goal 3 – Protocol Results 5 – Freespace Optic Quantum Channel 2KM Attenuation

Results from the fifth scenario of goal 3 was setup on a Freespace Optic channel with a distance of 2km between sender A and receiver B. Controller C was situated at half the distance 1.0km from both the sender and receiver. An intruder was also situated at 1.0km between the sender and receiver. The Freespace Optic quantum channel has an attenuation error rate with attenuation of freespace in dB/km; default: 87 dB/km. Compared to result 3 and 4 of the goal 3 evaluated the intruder also got random noise from the interception, however the receiver's image was better than that observed on the fibre, though still showed a compromise, the results were a little bit clearer compared to result 4.
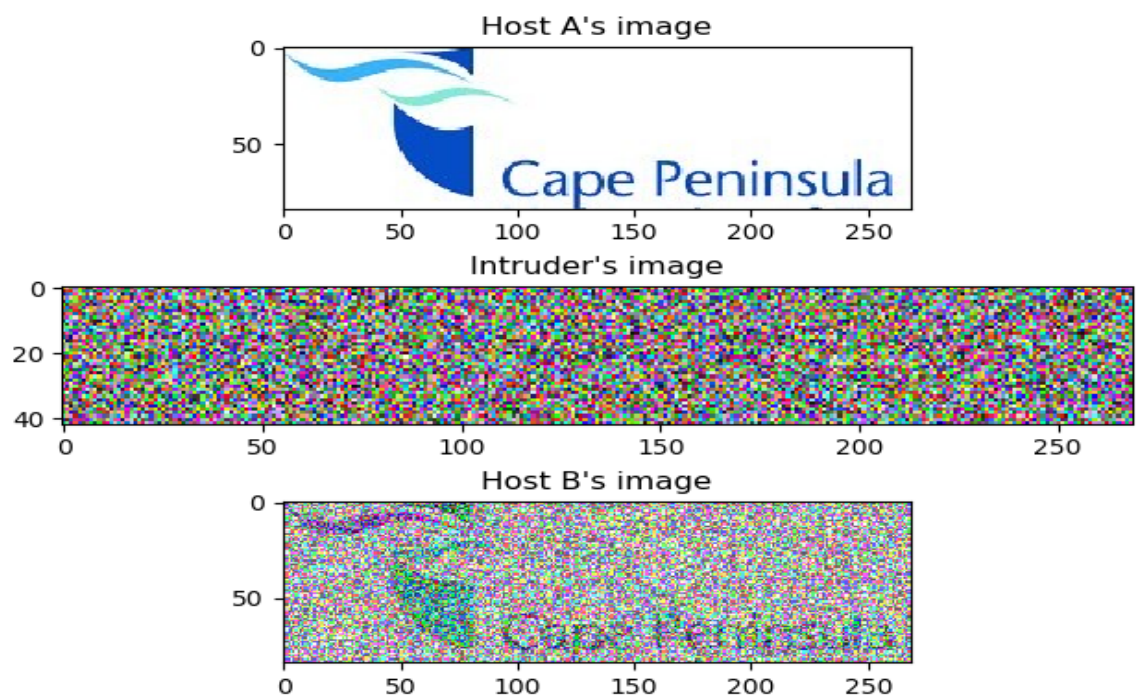
Figure 5.21 QT With Intruder Freespace

The snippet was as below:

```
# Connect the agents over simulated Freespace optic Base station
hosta.qconnect(hostb, FreeSpaceOpticQChannel, length=2.0)
hosta.qconnect(hoste, FreeSpaceOpticQChannel, length=1.0)
hosta.qconnect(hostc, FreeSpaceOpticQChannel, length=1.0)
hostb.qconnect(hostc, FreeSpaceOpticQChannel, length=1.0)
hostb.qconnect(hoste, FreeSpaceOpticQChannel, length=1.0)
# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()
# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

5.9 Conclusion

This chapter addressed research objective 2 (RO2 - to analyse the effect of using QT to securely transmit information). The development phase in the primary design research cycle was described where the research and data collection processes to compile the SecureQT-Framework were discussed. The development of the experiment ran in parallel with the development of the framework in which four sub-cycles of the design research each representing the phases (problem awareness, suggestion and development) were completed.

1. A study was conducted making use of literature review to identify QT technologies that are effective in the secure transmission of information.
2. A plan was outlined based on the literature review to setup the environment to evaluate the QT technologies effect as identified.
3. List of activities involved the installation, setup and configuration of relevant tools for the evaluation were presented.
4. Goals were outlined from planning to execution.
5. The goals were described to address research question 1 (RQ1) and subsequent sub-research questions (SRQ1, SRQ2 and SRQ3).

In this chapter one could also briefly show the linkages between Objectives, research questions and goals and how they the results would answer them. The development code used for the evaluation is outlined in detail within appendix A. the code will be packaged and distributed to the open source community as per the objectives of open source usage. The researcher has modified the code within the core framework of SQUANCH in which classes and modules were added to fit the research purposes. These changes or modifications included updates on core errors.py module as well as channels.py modules. The classes for Freespace optic quantum channels were added as well as registering attenuation errors within the freespace optics channels.

The next chapter provides the conclusion with discussion and reflection on the design and development of the Secure-QT-Framework.

CHAPTER SIX
CONCLUSIONS – DISCUSSION AND REFLECTION

Conclusion with Reflection and Abstraction on the SecureQT-Framework

Chapter four and five detailed the design and build of the framework artefact as well as using a simulated experiment with scenarios to evaluate the artefact. The chapter ends the research with abstraction and reflection on the SecureQT-framework artefact.

6.1   Introduction

This chapter articulates and presents the discussion, research contribution on the fulfilment of the outlined research objectives. This is where our abstraction and reflection of the knowledge contribution with regards to DSR research process is described. The constraints and limitation of this study is outlined as well as recommendations for future research.

6.2   Summary of the thesis

This thesis presented a research problem which stated that DC intercommunication data networks suffer from exploitation by cyber criminals. The exploitation may be as a result of the published vulnerabilities and the network security problems on OSI's Data Link Layer (Layer 2) that are said to have not been adequately addressed and in dire need for a redress. It was argued that the security gap for DC's intercommunication can be bridged by implementing QT techniques as it will make it even harder for anyone attempting to exploit the information while in transit. A need arose to provide empirical evidence that QT techniques have an effect on improving security of information between DC's on the WAN infrastructure in order to adequately propose a framework for their implementation. The research aim was to investigate the effect of QT on the improvement of DC communication security over the WAN for Layer 2 technologies.

Three research objectives were outlined which are:
- To design and develop the QT framework for use on Layer 2.
- To analyse the effect of using QT to securely transmit information.
- Propose a framework for the implementation of secure QT infrastructures for DC's.

The main research question was articulated as "How can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DC's?" this was followed by three research sub-questions which said:
- What QT frameworks and protocols exists to address security challenges for DC's Intercommunication over the WAN?

- How do these recognized solutions in SRQ1 differ within the approach they address the issues from the perspective of either the utilization of constraints, methodologies or techniques, and what quality of evidence in support of each solution?
- What implications do these solutions in SRQ2 have in the design and development of secure QT frameworks for DC's Intercommunication over the WAN?

6.3 Fulfilment of the research objectives

This study focused on how can, the use of QT be applied in the design and development of a framework to improve security over the wide area networks for DC's? Sub-questions has assisted in finding valuable answers on how to propose a framework for the implementation of secure quantum teleportation infrastructures in South Africa. This section explicitly show how the research questions were answered.

6.3.1 What QT Frameworks and Protocols Exists to Address Security Challenges for DCs Intercommunication over the WAN?

The literature has vast number of protocols and framework protocols that can be used to address the security challenges in the WAN. The following search strings were defined in the systematic literature survey:

Title contains: (quantum teleportation OR entanglement OR quantum communication OR quantum information processing) AND **Any field contains**: (secure OR physical OR discrete OR continuous OR hybrid OR wireless network OR SDN OR Transmission) AND **Subject contains**: (computer science OR information technology OR information theory OR quantum theory OR entanglement OR cryptography OR information processing OR quantum computing). The search was conducted between 2012 and 2018. An SLR was used to rigorously search and identify relevant QT frameworks and protocols that can be used to address the security gap on the WAN.

Section 2.3.4.2 under QT-approach, three sub-categories are outlined as approaches to physically implement QT, highlighting a single approach or a combination of the approaches to realise secure quantum teleportation implementation. under Variants/ Subtrates/ techniques, sixteen subcategories are outlined and further breakdown, these can be used to physically implement secure QT, it was noted as argued by (Ulrik L. Andersen et al., 2014; Guzman-silva et al., 2015; Guzman-Silva et al., 2017) that some of the subtrates are technologies while others can be protocols. Under WAN infrastructure, five sub-categories are outlined that shows capability of QT to run on the current or enhanced infrastructure to allow secure communication over the WAN.QT

has been extended in various ways that include but not limited to all-optical QT, QT networks, single photon states QT, quantum gate teleportation, QT channels and entanglement QT known as entanglement swapping.

6.3.2 How do these recognized solutions in SRQ1 differ within the approach they address the issues from the perspective of either the utilization of constraints, methodologies or techniques, and what quality of evidence in support of each solution?

The primary studies selected have highlighted limitations across the technologies, some of the limitations in no particular order that applies to the majority of QT approaches i.e. DV, CV and Hybrid can be listed as: decoherence, interference, transmission loss, atmospheric absorption, refraction and multipath, freespace loss, sky or ground wave propagation; and line-of-sight propagation. The QT technologies as identified by primary studies: DV and CV historically followed two complementary approaches to QT with the latest hybrid schemes that seek to integrate the two approaches. These approaches as identified uses different WAN infrastructure approaches such as Satellite, Fibre Optics, SDN, Free-Space Optics, and Microwave. Satellite infrastructure over the WAN has been realised for QT and in process of rigorous testing for commercialization. Fiber Optics infrastructure has proven to be realizable for MAN and support QT protocols. SDN have been proven to be realizable for QT and paving a way for applicability to cloud and data centres that will eventually lead to quantum internet applicability. Freespace optics infrastructure have proven to be realizable and support QT protocols paving a way for its low cost alternative for WAN infrastructure to be deployed across DCs. Microwave technology looks promising for MAN deployment, however still needs more proven results for its applicability for fully implementing QT protocols. Photonic qubits have gained more focus and momentum with more articles experimenting, based on its capability and realization in practice. NMR seems to have not had much attention as few articles and experiments are reported around this technology. Optical modes have gained more focus as they can be implemented across various approaches, methods, and channels. Atomic ensembles are proving to be of great use in teleportation and entanglement swapping involving bosonic systems of different nature that help enhance hybrid entanglement. Trapped atoms technologies are still going under testing though have proven to be applicable into MAN networks through microwave infrastructure. Solid state technology has proved to be reliable and can be used in quantum circuits and quantum repeaters and allows use of hybrid protocols.

6.3.3 What implications do these solutions in SRQ2 have in the design and development of secure QT frameworks for DCs Intercommunication over the WAN?

There seems to be no particular technology as a standalone that can satisfy all the requirements, however from the studies we have learnt that photonic qubits and optical modes are leading technologies in terms of WAN transmission, though they need to be strengthened by technologies such as solid state, trapped atoms and atomic ensembles for hybrid entanglement in order to enable quantum repeaters to extend the distance of coverage. We also argue that SDN has the potential to bridge the gap in secure transmission and implementation, especially for cloud and data centre technologies, SDN technologies through open source have proved to provide a great framework to design, develop and test QT protocols and its theoretical underpinnings. The tools presented by SDNs afford us an opportunity to simulate QT to prove the theoretical principles proposed within various articles and conference proceedings. We have studied and found that there is a lack of generic frameworks that can be used to guide the selection and implementation of QT technologies.

6.4 Key Contributions

The key contribution of the study is the design, build and assessment of an abstract SecureQT-Framework artefact (a framework that can be used in determining which quantum teleportation infrastructure to implement in the particular circumstance that will yield the most benefit to Data Centres in South Africa, comprising of models and methods). The proposed artefact allows the implementation of appropriate quantum information and communication delivery platforms, and enables the secure transmission of information based on quantum physics laws and further based on the data centre's needs. The data centres may range from South African military bases, Department of Defence, Department of Telecommunication and postal services, Health and Finance industry, etc.

The contributions to information system body of knowledge can be described as:
- The application of quantum physics and computer science to deal strictly with the Layer 2 transmission security issues within the existing data centres.
- The use of DSR to design, develop and evaluate a framework for use in implementing quantum teleportation infrastructures.

The information systems practice contribution can be described as:
- The understanding of how data centres can improve data transmission security by implementing QT infrastructures.
- The framework for implementing QT infrastructures with expected benefits of security when transmitting information.

- The use of Software Defined Networks and Python API in simulation and validating the concepts of quantum teleportation.

Further the quantum teleportation models on the framework can be used by researchers, academics as the basis for Information and Cyber security enhancements.

6.4.1 Literature Review

Literature review on quantum teleportation with relevance to the research was rigorously conducted; it drew from academic journals, scholarly articles, websites, and published literature sources. The study further reviewed the main role of quantum teleportation using quantum entanglement to securely transmit information between communicating data centres.

The SLR was undertaken to:

- Gather and interpret empirical evidence within the available QT research.
- Compare the solutions with respect to constraints, methods and/or approaches to QT, and identify strengths of the evidence in support of the different solutions found.
- Describe the implications of the findings when creating solutions.

According to (Okoli, 2017; Okoli & Schabram, 2010) an SLR can be described as "a systematic, explicit, comprehensive, and reproducible method for identifying, evaluating, and synthesizing the existing body of completed and recorded work produced by researchers, scholars, and practitioners." SLR ensured that our study followed a defined plan in which the criterion is clearly stated before conducting the review. This allowed a transparent and comprehensive search over multiple literature sources that can be reproducible by other researchers. We therefore outlined the search terms and strategies that include search engines, platforms and search dates outlining all exclusions and inclusions.

6.4.2 Research Methodology

DSR was selected as the methodology for this research. According to (Venable et al., 2016) DSR is defined as a research that "invents a new purposeful artefact to address a generalised type of problem and evaluates its utility for solving problems of that type." DSR is an accepted research paradigm and an approach in the Information System (IS) field, aiming at developing purposeful IT artefacts and knowledge about the design of IT artefacts (Peffers et al., 2012; Gregor & Hevner, 2013).

6.4.3 Simulated Experiment

The use of Experiment designs in terms of computer simulation experiment provided the structure for the researcher's learning process. The computer simulation was used to investigate the relationship of the response to the factors under quantum teleportation research to define the fundamental mechanisms governing the process as outlined by (Hunter & Naylor, 1969). The SecureQT-Framework artefact took the form of Simulation to execute the artefact with artificial data and involved the use of *hypothetical scenarios* to get around the issues of real-world access to application while still providing convincing evidence and be able to construct detailed scenarios around the artefact to demonstrate its usefulness. Using Scenarios was a good path to pursue as forced scenario grounds the artefact in a specific context without relying on generalization.

6.4.4 Proposed SecureQT-Framework

The proposed generic SecureQT-Framework to guide the implementation of secure teleportation infrastructures in South Africa consisted of a Model and method which was thus described and presented. The proposed framework was rigorously evaluated and contains features that are distinct to itsself namely inherent security, dynamicity, integration and adaptability to changing environment and technology landscape. The SecureQT-Framework fits exactly on what Purao (2002) described as operational principles in which he emphasized artefacts which specify how things can be done in a reproducible manner. We have presented this model and method in the South African context however it can be adopted by any other country or state that wishes to apply the framework.

The proposed generic SecureQT-Frameworks model consisted of five phases, namely:

- Phase A – Delivery Model
- Phase B – Planning and Investigation
- Phase C – Knowledge Base
- Phase D – Methodology and Approach
- Phase E – Quantum Technology

The five phases are supported by a four continuous methodology process namely:
- Explore Foundations – foundations in the knowledge base
- Determine and Apply – gained knowledge from knowledge base
- Implement and Evaluate – the methodology and approach
- Monitor and Maintain – the technology implementation

The SecureQT-Framework presents a technology-independent approach to the implementation of secure quantum teleportation infrastructures with unique foundational building blocks. The generic framework makes use of knowledge base as a centre of excellence with regards to foundational knowledge ranging from Quantum Physics, Computer Science, Information and Communication Technology. The knowledge base also contains categories for physical quantum teleportation implementation as well as Wide Area Network infrastructures that may be applicable to a specific physical quantum communication implementation.

When compared to the basic artefacts on what make-up DSR as proposed by (Hevner & Chatterjee, 2004), as outlined in section 3.4.2 SecureQT-Framework satisfies the requirement of a purposeful artefact. It's usefulness to guide the identification and implementation of secure teleportation infrastructures was illustrated by hypothetical scenarios. The framework could also be seen as an "invention"; in that it demonstrates improvement to the multiple QT approaches by introducing a generic standardised model and method. The artefact fulfils the evaluation as described by Venable and Baskerville (2012). As discussed in chapter 5, we assessed the artefact using various approaches, one which is a descriptive and experimental evaluation, where we developed and simulated scenarios around a hypothetical goal statement. The other which is evaluation based on argumentation.

This study agrees with Hevner et al. (2004) as he argued that "IS research needs to be rigorous" to contribute knowledge to the knowledge base and relevance, for application in the appropriate setting. Therefore this study fits to both descriptive and prescriptive knowledge as argued by Gregor and Hevner (2013:343) that DSR should comprise both types of knowledge. We can map the study's knowledge contribution into the improvement quadrant as discussed in section 2.6, there is still no widely adopted generic framework to guide the implementation of quantum teleportation infrastructures with a model and a method. Therefore this research becomes an addition to the current body of quantum teleportation and information systems knowledge using the design science research paradigm.

6.5 Recommendation and Limitations

The limitation to this study is that SecureQT-Framework artefact has not been tested in a real-world scenario only simulated reality was applied, though argued that scientific justification can be used in the development of solutions to complex problems in the field (Van Aken, 2005). Further limitations were due to time constraints in which other scenarios were not evaluated that includes end-to-end simulation of QT using fully

software defined networks. The study also had a limitation in touching areas of "quantum error correction" and "quantum repeaters".

The study recommends a further area of research in the use of software defined networks using the DSR approach, this will prove fruitful for agencies and academic institutions to test and evaluate the possibilities of secure data transmission in the era of quantum communication which is the future of secure data transmission. The researcher has further interests in writing and publishing a number of journal and scholarly articles to present to conferences and seminars. This will assist with more engagements to discuss or critique the results and observations made to both academia and the practitioner community.

6.6   Conclusion

A detailed discussion was presented in the design and building of the SecureQT-Framework to guide the implementation of teleportation infrastructures using a model and a method. Systematic literature survey was done to ensure the research has rigour, DSR approach was used as a paradigm and followed the outlined five phases to meet the goals of this study. The particular needs for South Africa were taken into consideration when developing the framework. The framework will also assist in adopting new standards for cybersecurity in the country.

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APPENDICES

APPENDIX A: MININET-WIFI SDN CODE

ClassicalSniffing.py

```python
#!/usr/bin/python

from mininet.node import Controller, Host
from mininet.log import setLogLevel, info
from mn_wifi.net import Mininet_wifi
from mn_wifi.node import Station, OVSKernelAP
from mn_wifi.cli import CLI_wifi
from mn_wifi.link import wmediumd
from mn_wifi.wmediumdConnector import interference
from subprocess import call

def myNetwork():

    net = Mininet_wifi(topo=None,
                       listenPort=1114,
                       build=False,
                       link=wmediumd,
                       wmediumd_mode=interference,
                       ipBase='10.0.0.0/8')

    info( '*** Adding controller\n' )
    c0 = net.addController(name='c0',
                      controller=Controller,
                      protocol='tcp',
                      port=6633)

    info( '*** Add switches/APs\n')
    ap1 = net.addAccessPoint('ap1', cls=OVSKernelAP, ssid='ap1-ssid',
                         channel='1', mode='g', position='416.0,327.0,0')
    ap2 = net.addAccessPoint('ap2', cls=OVSKernelAP, ssid='ap2-ssid',
                         channel='1', mode='g', position='994.0,326.0,0')

    info( '*** Add hosts/stations\n')
    h2 = net.addHost('h2', cls=Host, ip='10.0.0.2', defaultRoute=None)
    sta1 = net.addStation('sta1', ip='10.0.0.1',
                   position='536.0,462.0,0')
    h1 = net.addHost('h1', cls=Host, ip='10.0.0.1', defaultRoute=None)
    sta2 = net.addStation('sta2', ip='10.0.0.2',
                   position='1138.0,457.0,0')

    info("*** Configuring Propagation Model\n")
    net.setPropagationModel(model="logDistance", exp=3)

    info("*** Configuring wifi nodes\n")
    net.configureWifiNodes()

    info( '*** Add links\n')
    net.addLink(h1, ap1)
    net.addLink(sta1, ap1)
    net.addLink(h2, ap2)
    net.addLink(sta2, ap2)
    net.addLink(ap1, ap2)

    net.plotGraph(max_x=1000, max_y=1000)

    info( '*** Starting network\n')
    net.build()
    info( '*** Starting controllers\n')
    for controller in net.controllers:
        controller.start()

    info( '*** Starting switches/APs\n')
    net.get('ap1').start([c0])
    net.get('ap2').start([c0])

    info( '*** Post configure nodes\n')

    CLI_wifi(net)
    net.stop()

if __name__ == '__main__':
```

```
setLogLevel( 'info' )
myNetwork()
```

APPENDIX B: QUANTUM TELEPORTATION-SQUANCH CODE

The SQUANCH Code as adapted from the SQUANCH framework by (Bartlett, 2018b; Bartlett, 2018a)

Core Framework Updated Modules Errors and Channels.

Channels.py

```python
class FreeSpaceOpticQChannel(QChannel):
    '''   Represents a freespace Optic path loss in dB     '''
    def __init__(self, from_agent, to_agent, length = 2.0):
        '''
        Instantiate the simulated  Freespace Optic quantum channel
        :param Agent from_agent: sending agent
        :param Agent to_agent: receiving agent
        :param float length: length of freespace optic channel in km; default: 2.0km
        '''
        QChannel.__init__(self, from_agent, to_agent, length = length)
        # Register  errors
        self.errors = [
            errors.FreeSpaceAttenuationError(self),
        ]
```

Errors.py

```python
class FreeSpaceAttenuationError(QError):
    '''Simulate the possible loss of a qubit in a freespace optic channel due to attenuation effects - Themba Ngobeni as part of
Masters research'''

    def __init__(self, qchannel, attenuation_coefficient = 87):
        '''
        Instantiate the error class

        :param QChannel qchannel: parent quantum channel
        :param float attenuation_coefficient: attenuation of freespace in dB/km; default: 87 dB/km
        '''
        QError.__init__(self, qchannel)

        #Variable declaration
        hb=100 #in feets(height of BS antenna)
        hm=5  # in feets(height of mobile antenna)
        f=881.52#in MHz
        lamda=1.116  #in feet
        d=5000  #in feet
        Gb=10**0.8  #8dB(BS antenna gain)
        Gm=10**0   # 0dB (Mobile antenna gain)

        #Calculations&Results
        free_atten=(4*math.pi*d/lamda)**2*(Gb*Gm)**-1
        y=round(10*math.log10(free_atten))
        print ("FreeSpace Optic attenuation is '{}'. dB".format(y))
        reflect_atten= (d**4/(hb*hm)**2)*(Gb*Gm)**-1
        x=round(10*math.log10(reflect_atten))
        #print ("Reflecting surface attenuation is '{}'. dB ".format(x))
        #decibel_loss = qchannel.length * y
        self.attenuation = y  # Total attenuation along the freespace

    def apply(self, qubit):
        '''
        Simulates possible loss + measurement of qubit

        :param Qubit qubit: qubit from quantum channel
        :return: either unchanged qubit or None
        '''
        if np.random.rand() > self.attenuation and qubit is not None:
            # Photon was lost due to attenuation effects; collapse state and return nothing
            print ("FreeSpace Optic attenuation is '{}'. dB".format(self.attenuation))
            qubit.measure()
            qubit = None
        return qubit
```

SecureQT-StringTeleport.py

```python
#!/usr/bin/python3.6
from squanch import *
import sys
```

```
class HostA(Agent):
    def run(self):
        for qsys, bit in zip(self.qstream, self.data):
            q, = qsys.qubits
            if bit == "1": X(q)
            self.qsend(hostb, q)

class HostB(Agent):
    def run(self):
        bits = ""
        for _ in self.qstream:
            q = self.qrecv(hosta)
            bits += str(q.measure())
        self.output(bits)

def bits_to_string(bits):
# Return a message from a binary string
    msg = ""
    for i in range(0, len(bits), 8):
        digits = bits[i:i + 8]
        msg += chr(int(digits, 2))
    return msg

def string_to_bits(msg):
# Return a string of 0's and 1's from a message
    bits = ""
    for char in msg: bits += "{:08b}".format(ord(char))
    return bits

msg = str(sys.argv[1])
bits = string_to_bits(msg)

qstream = QStream(1, len(bits))
out = Agent.shared_output()

hosta = HostA(qstream, data = bits)
print("Host-A sent: '{}'.".format(msg))
print("Host-A Message Bits: '{}'.".format(bits))

hostb = HostB(qstream, out = out)
print("Teleporting Quantum State to Host-B.")

hosta.qconnect(hostb)
hosta.cconnect(hostb)

hosta.start()
hostb.start()
hosta.join()
hostb.join()

received_msg = bits_to_string(out["HostB"])
print("Host-B Message Bits: '{}'.".format(string_to_bits(received_msg)))
print("Host-B received: '{}'.".format(received_msg))
```

SecureQT-Simulation.py

```
#!/usr/bin/python3.6
import numpy as np
import matplotlib.image as image
import matplotlib.pyplot as plt
from squanch import *

class hostC(Agent):
    '''Host-C as Originator/controller sends Bell pairs to Host-A and Host-B'''
    def run(self):
        for qsys in self.qstream:
            a, b = qsys.qubits
            H(a)
            CNOT(a, b)
            self.qsend(hosta, a)
            self.qsend(hostb, b)

class hostA(Agent):
    '''Host-A tries to send data to Host-B, but Host-E intruder intercepts before reaching B'''
    def run(self):
        for _ in self.qstream:
```

```
                bit1 = self.data.pop(0)
                bit2 = self.data.pop(0)
                q = self.qrecv(hostc)
                    if q is not None:
                    if bit2 == 1: X(q)
                    if bit1 == 1: Z(q)
                # Host-A unknowingly sends the qubit to Intruder Host-E
                self.qsend(hoste, q)

class hostE(Agent):
    '''Host-E naively tries to intercept Host-A's data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hosta)
            bits.append(a.measure())
            self.qsend(hostb, a)
        self.output(bits)

class hostB(Agent):
    '''Host-B receives Intruder's intercepted data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hoste)
            c = self.qrecv(hostc)
            CNOT(a, c)
            H(a)
            bits.extend([a.measure(), c.measure()])
        self.output(bits)

#https://realpython.com/python-matplotlib-guide/
#https://matplotlib.org/3.1.0/gallery/subplots_axes_and_figures/subplots_demo.html
def plot_images(hoste_bits, hostb_bits):
    hoste_img = np.reshape(np.packbits(hoste_bits), (int(img.shape[0]/2), img.shape[1], img.shape[2]))
    print("Intruder bitsreamlength {}".format((int(img.shape[0]/2), img.shape[1], img.shape[2])))
    hostb_img = np.reshape(np.packbits(hostb_bits), img.shape)
    print("Host-B bitsreamlength {}".format(len(hostb_img)))
    #f, ax = plt.subplots(1, 3, figsize = (18, 9))
    f, ax = plt.subplots(3)
    ax[0].imshow(img)
    ax[0].axis('on')
    ax[0].title.set_text("Host A's image")
    ax[1].imshow(hoste_img)
    ax[1].axis('on')
    ax[1].title.set_text("Intruder's image")
    ax[2].imshow(hostb_img)
    ax[2].axis('on')
    ax[2].title.set_text("Host B's image")
    print("\n Complete Simulation Results")
    plt.tight_layout()
    plt.show()

# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())
print("Bitstream {}".format(len(bitstream)))


# Prepare an appropriately sized quantum stream
qstream = QStream(2, int(len(bitstream) / 2))
out = Agent.shared_output()

# Instantiate agents
hosta = hostA(qstream, out, data=bitstream)
hostb = hostB(qstream, out)
hostc = hostC(qstream, out)
hoste = hostE(qstream, out)

# Connect the agents to form the network
hosta.qconnect(hostb)
hosta.qconnect(hoste)
hosta.qconnect(hostc)
hostb.qconnect(hostc)
hostb.qconnect(hoste)

# Set photon transmission rate
hosta.pulse_length = 1e-9
```

```
hostb.pulse_length = 1e-9
hoste.pulse_length = 1e-9
hostc.pulse_length = 1e-9

# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()

# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

SecureQT-Simulation-PlotText.py

```
#!/usr/bin/python3.6
from squanch import *
import numpy as np
import matplotlib.image as image
import matplotlib.pyplot as plt

class HostA(Agent):
    '''Alice sends qubits to Bob using a shared Bell pair'''

    def distribute_bell_pair(self, a, b):
        # Create a Bell pair and send one particle to HostB
        H(a)
        CNOT(a, b)
        self.qsend(hostb, b)

    def teleport(self, q, a):
        # Perform the teleportation
        CNOT(q, a)
        H(q)
        # Tell HostB whether to apply Pauli-X and Pauli-Z over classical channel
        apply_x = a.measure() # if B should apply X
        apply_z = q.measure() # if B should apply Z
        self.csend(hostb, [apply_x, apply_z])

    def run(self):
        for qsystem in self.qstream:
            q, a, b = qsystem.qubits # q is state to teleport, a and b are Bell pair
            self.distribute_bell_pair(a, b)
            self.teleport(q, a)


class HostB(Agent):
    '''Host-B receives qubits from Host-A and measures the results'''

    def run(self):
        measurement_results = []
        for _ in self.qstream:
            # B receives a qubit from A
            b = self.qrecv(hosta)
            # B receives classical instructions from A
            apply_x, apply_z = self.crecv(hosta)
            if apply_x: X(b)
            if apply_z: Z(b)
            # Measure the output state
            measurement_results.append(b.measure())
        # Put results in output object
        self.output(measurement_results)


# Prepare the initial states
qstream = QStream(3,30) # 3 qubits per trial, 30 trials
states_to_teleport = [1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 1, 1, 0, 1, 0, 1, 0, 1, 1, 0, 0, 1, 1, 0, 0, 0, 0]
for state, qsystem in zip(states_to_teleport, qstream):
    q = qsystem.qubit(0)
    if state == 1: X(q) # flip the qubits corresponding to 1 states




# Make and connect the agents
out = Agent.shared_output()
hosta = HostA(qstream, out)
hostb = HostB(qstream, out)
hosta.qconnect(hostb) # add a quantum channel
hosta.cconnect(hostb) # add a classical channel



# Run everything
```

```
hosta.start()
hostb.start()
hosta.join()
hostb.join()

print("Host-A Teleported states {}".format(states_to_teleport))
print("Host-B Received states   {}".format(out["HostB"]))


angles = np.linspace(0, 2 * np.pi, 45)  # RX angles to apply
num_trials = 250                  # number of trials for each angle

# Prepare the initial states in the stream
qstream = QStream(3, len(angles) * num_trials)
for angle in angles:
    for _ in range(num_trials):
        q, _, _ = qstream.next().qubits
        RX(q, angle)

# Make the agents and connect with quantum and classical channels
out = Agent.shared_output()
hosta = HostA(qstream, out = out)
hostb = HostB(qstream, out = out)
hosta.qconnect(hostb)
hosta.cconnect(hostb)

# Run the simulation
Simulation(hosta, hostb).run()

# Plot the results
results = np.array(out["HostB"]).reshape((len(angles), num_trials))
observed = np.mean(results, axis = 1)
expected = np.sin(angles / 2) ** 2
plt.plot(angles, observed, label = 'Observed')
plt.plot(angles, expected, label = 'Expected')
plt.legend()
plt.xlabel("$\Theta$ in $R_X(\Theta)$ applied to qubits")
plt.ylabel("Fractional $\left | 1 \\right >$ population")
plt.show()
```

SecureQT-Simulation2.py

```
#!/usr/bin/python3.6
import numpy as np
import matplotlib.image as image
import matplotlib.pyplot as plt
from squanch import *

class hostC(Agent):
    '''Host-C as Originator/controller sends Bell pairs to Host-A and Host-B'''
    def run(self):
        for qsys in self.qstream:
            a, b = qsys.qubits
            H(a)
            CNOT(a, b)
            self.qsend(hosta, a)
            self.qsend(hostb, b)

class hostA(Agent):
    '''Host-A tries to send data to Host-B, but Hot-E intruder intercepts before reaching B'''
    def run(self):
        for _ in self.qstream:
            b1 = self.data.pop(0)
            b2 = self.data.pop(0)
            q = self.qrecv(hostc)
            if q is not None:
                if b2 == 1: X(q)
                if b1 == 1: Z(q)
            # Host-A sends the qubit to Host-B
            self.qsend(hostb, q)


class hostB(Agent):
    '''Host-B receives Intruder's intercepted data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hosta)
            c = self.qrecv(hostc)
```

```
            if a is not None and c is not None:
                CNOT(a, c)
                H(a)
                bits.extend([a.measure(), c.measure()])
            else:
                bits.extend([0,0])
        self.output(bits)

#https://realpython.com/python-matplotlib-guide/
#https://matplotlib.org/3.1.0/gallery/subplots_axes_and_figures/subplots_demo.html
def plot_images(hostb_bits):
    hostb_img = np.reshape(np.packbits(hostb_bits), img.shape)
    #f, ax = plt.subplots(1, 2, figsize = (18, 9))
    f, ax = plt.subplots(2)
    ax[0].imshow(img)
    ax[0].axis('on')
    ax[0].title.set_text("Host A's image")
    ax[1].imshow(hostb_img)
    ax[1].axis('on')
    ax[1].title.set_text("Host B's image")
    print("\nComplete Simulation Results")
    plt.tight_layout()
    plt.show()

# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())


# Prepare an appropriately sized quantum stream
qstream = QStream(2, int(len(bitstream) / 2))
out = Agent.shared_output()

# Instantiate agents
hosta = hostA(qstream, out, data=bitstream)
hostb = hostB(qstream, out)
hostc = hostC(qstream, out)

# Connect the agents to form the network
hosta.qconnect(hostb)
hostc.qconnect(hosta)
hostc.qconnect(hostb)


# Set photon transmission rate
#hosta.pulse_length = 1e-9
#hostb.pulse_length = 1e-9
#hostc.pulse_length = 1e-9

# Run the simulation
Simulation(hosta, hostb, hostc).run()

# Display the images hostA sent and hostB received
plot_images(out["hostB"])
```

SecureQT-Simulation3.py

```
#!/usr/bin/python3.6
import numpy as np
import matplotlib.image as image
import matplotlib.pyplot as plt
from squanch import *

class hostC(Agent):
    '''Host-C as Originator/controller sends Bell pairs to Host-A and Host-B'''
    def run(self):
        for qsys in self.qstream:
            a, b = qsys.qubits
            H(a)
            CNOT(a, b)
            self.qsend(hosta, a)
            self.qsend(hostb, b)


class hostA(Agent):
    '''Host-A tries to send data to Host-B, but Host-E intruder intercepts before reaching B'''
    def run(self):
        for _ in self.qstream:
            bit1 = self.data.pop(0)
```

```python
            bit2 = self.data.pop(0)
            q = self.qrecv(hostc)
            if q is not None:
                if bit2 == 1: X(q)
                if bit1 == 1: Z(q)
            else:
                bit1 = 0
                bit2 = 0
            # Host-A unknowingly sends the qubit to Intruder Host-E
            self.qsend(hoste, q)

class hostE(Agent):
    '''Host-E naively tries to intercept Host-A's data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hosta)
            if a is not None:
                bits.append(a.measure())
            else:
                bits.append(0)
            self.qsend(hostb, a)
        self.output(bits)

class hostB(Agent):
    '''Host-B receives Intruder's intercepted data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hoste)
            c = self.qrecv(hostc)
            if a is not None and c is not None:
                CNOT(a, c)
                H(a)
                bits.extend([a.measure(), c.measure()])
            else:
                bits.extend([0,0])
        self.output(bits)

#https://realpython.com/python-matplotlib-guide/
#https://matplotlib.org/3.1.0/gallery/subplots_axes_and_figures/subplots_demo.html
def plot_images(hoste_bits, hostb_bits):
    hoste_img = np.reshape(np.packbits(hoste_bits), (int(img.shape[0]/2), img.shape[1], img.shape[2]))
    print("Intruder bitsreamlength {}".format((int(img.shape[0]/2), img.shape[1], img.shape[2])))
    hostb_img = np.reshape(np.packbits(hostb_bits), img.shape)
    print("Host-B bitsreamlength {}".format(len(hostb_img)))
    #f, ax = plt.subplots(1, 3, figsize = (18, 9))
    f, ax = plt.subplots(3)
    ax[0].imshow(img)
    ax[0].axis('on')
    ax[0].title.set_text("Host A's image")
    ax[1].imshow(hoste_img)
    ax[1].axis('on')
    ax[1].title.set_text("Intruder's image")
    ax[2].imshow(hostb_img)
    ax[2].axis('on')
    ax[2].title.set_text("Host B's image")
    print("\n Complete Simulation Results")
    plt.tight_layout()
    plt.show()

# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())
print("Bitstream {}".format(len(bitstream)))


# Prepare an appropriately sized quantum stream
qstream = QStream(2, int(len(bitstream) / 2))
out = Agent.shared_output()

# Instantiate agents
hosta = hostA(qstream, out, data=bitstream)
hostb = hostB(qstream, out)
hostc = hostC(qstream, out)
hoste = hostE(qstream, out)

# Connect the agents to form the network
```

```
#hosta.qconnect(hostb)
#hosta.qconnect(hoste)
#hosta.qconnect(hostc)
#hostb.qconnect(hostc)
#hostb.qconnect(hoste)

# Set photon transmission rate
hosta.pulse_length = 1e-9
hostb.pulse_length = 1e-9
hoste.pulse_length = 1e-9
hostc.pulse_length = 1e-9

# Connect the agents over simulated fibre optic lines
hosta.qconnect(hostb, FiberOpticQChannel, length=5.0)
hosta.qconnect(hoste, FiberOpticQChannel, length=2.5)
hosta.qconnect(hostc, FiberOpticQChannel, length=2.5)
hostb.qconnect(hostc, FiberOpticQChannel, length=2.5)
hostb.qconnect(hoste, FiberOpticQChannel, length=2.5)

# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()

# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```

SecureQT-Simulation4.py

```python
#!/usr/bin/python3.6
import numpy as np
import matplotlib.image as image
import matplotlib.pyplot as plt
from squanch import *

class hostC(Agent):
    '''Host-C as Originator/controller sends Bell pairs to Host-A and Host-B'''
    def run(self):
        for qsys in self.qstream:
            a, b = qsys.qubits
            H(a)
            CNOT(a, b)
            self.qsend(hosta, a)
            self.qsend(hostb, b)

class hostA(Agent):
    '''Host-A tries to send data to Host-B, but Host-E intruder intercepts before reaching B'''
    def run(self):
        for _ in self.qstream:
            bit1 = self.data.pop(0)
            bit2 = self.data.pop(0)
            q = self.qrecv(hostc)
            if q is not None:
                if bit2 == 1: X(q)
                if bit1 == 1: Z(q)
            else:
                bit1 = 0
                bit2 = 0
            # Host-A unknowingly sends the qubit to Intruder Host-E
            self.qsend(hoste, q)

class hostE(Agent):
    '''Host-E naively tries to intercept Host-A's data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hosta)
            if a is not None:
                bits.append(a.measure())
            else:
                bits.append(0)
            self.qsend(hostb, a)
        self.output(bits)

class hostB(Agent):
    '''Host-B receives Intruder's intercepted data'''
    def run(self):
        bits = []
        for _ in self.qstream:
            a = self.qrecv(hoste)
            c = self.qrecv(hostc)
```

```python
        if a is not None and c is not None:
            CNOT(a, c)
            H(a)
            bits.extend([a.measure(), c.measure()])
        else:
            bits.extend([0,0])
    self.output(bits)

#https://realpython.com/python-matplotlib-guide/
#https://matplotlib.org/3.1.0/gallery/subplots_axes_and_figures/subplots_demo.html
def plot_images(hoste_bits, hostb_bits):
    hoste_img = np.reshape(np.packbits(hoste_bits), (int(img.shape[0]/2), img.shape[1], img.shape[2]))
    print("Intruder bitsreamlength {}".format((int(img.shape[0]/2), img.shape[1], img.shape[2])))
    hostb_img = np.reshape(np.packbits(hostb_bits), img.shape)
    print("Host-B bitsreamlength {}".format(len(hostb_img)))
    #f, ax = plt.subplots(1, 3, figsize = (18, 9))
    f, ax = plt.subplots(3)
    ax[0].imshow(img)
    ax[0].axis('on')
    ax[0].title.set_text("Host A's image")
    ax[1].imshow(hoste_img)
    ax[1].axis('on')
    ax[1].title.set_text("Intruder's image")
    ax[2].imshow(hostb_img)
    ax[2].axis('on')
    ax[2].title.set_text("Host B's image")
    print("\n Complete Simulation Results")
    plt.tight_layout()
    plt.show()

# Load Host-A's data (an image) and serialize it to a bitstream
img = image.imread("/home/squanch/cputLog.jpg")
bitstream = list(np.unpackbits(img))
#bitstream = list(img.flatten())
print("Bitstream {}".format(len(bitstream)))


# Prepare an appropriately sized quantum stream
qstream = QStream(2, int(len(bitstream) / 2))
out = Agent.shared_output()

# Instantiate agents
hosta = hostA(qstream, out, data=bitstream)
hostb = hostB(qstream, out)
hostc = hostC(qstream, out)
hoste = hostE(qstream, out)

# Connect the agents to form the network
#hosta.qconnect(hostb)
#hosta.qconnect(hoste)
#hosta.qconnect(hostc)
#hostb.qconnect(hostc)
#hostb.qconnect(hoste)

# Set photon transmission rate
hosta.pulse_length = 1e-9
hostb.pulse_length = 1e-9
hoste.pulse_length = 1e-9
hostc.pulse_length = 1e-9

# Connect the agents over simulated Freespace optic Base station
hosta.qconnect(hostb, FreeSpaceOpticQChannel, length=2.0)
hosta.qconnect(hoste, FreeSpaceOpticQChannel, length=1.0)
hosta.qconnect(hostc, FreeSpaceOpticQChannel, length=1.0)
hostb.qconnect(hostc, FreeSpaceOpticQChannel, length=1.0)
hostb.qconnect(hoste, FreeSpaceOpticQChannel, length=1.0)

# Run the simulation
Simulation(hosta, hoste, hostb, hostc).run()

# Display the images hostA sent, hostE intercepted, and hostB received
plot_images(out["hostE"], out["hostB"])
```