A Solace in Quantum

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ABSTRACT

Qubits, Atoms, Photons, Entanglements, Quantum Mechanics and Diamonds meet the Information Age. Current research indicates that diamonds may hold the key to a cryptanalyst's nightmare, 'The unbreakable cipher'. This paper introduces the basic theory and principles behind this innovative technology, reports on the research that has led to present day breakthroughs, investigates those that hold promise and looks at the possibilities for future research in this field. This report is presented as a primer to the 'World of Quantum Cryptography' and its impact on Network Security and Management. Consequently, it does not provide any mathematical proofs behind the theoretical models which relate to Quantum Mechanics. It does, however, make reference to and direct those who require this depth of knowledge to the sources if this information is desired or is the basis for further research.

Categories and Subject Descriptors

A.1 **[INTRODUCTORY AND SURVEY]**, D.4.6 **[Security and Protection]**: Access controls, Cryptographic controls, Information flow controls.

General Terms

Security, Standardization, and Theory

Keywords

Photons, basis, rectilinear, coherence, quantum, Heisenberg's principle, qubit, polarization, entanglement

1. INTRODUCTION

At an international conference held in Vienna on October 8, 2008, the Secure Communication based on Quantum Cryptography (SECOQC) [19] consortium introduced the world's largest and most intricate network, one which transmits quantum data encoded as qubits in the form of photons. This remarkable achievement is the result of several steps in technology, from those first proposed by Charles Bennett and Gilles Brassard [3] in 1984 to the quantum leaps in applied research of the past decade.

The network consists of eight fiber optic links that range between six and eighty-two kilometers in length and span approximately 200 kilometers in overall diameter [14]. It also includes provisions for two free-space Quantum Access Networks (QAN). The network is designed to generate and distribute cryptographic keys, Quantum-Key-Distribution (QKD) over a full mesh fiber optic Quantum Back Bone (QBB) in order to encode or decode data which is subsequently sent over a classic public channel.

A fundamental property of quantum mechanics, based on Heisenberg's uncertainty principle [1] (p.84), is that measuring a quantum state changes the nature of that quantum system. This theoretically makes data encoded as a quantum entity on the QBB impossible to view without physically altering its state, effectively resulting in QKD as an unconditionally secure scheme according to 'Classical Information Security Theory'. In order to validate the QKD network as a viable secure business solution, the SECOQC architecture incorporates several different state-of-the-art encoding schemes based on the controlled generation of light quanta, or photons. It is these technologies that will be reviewed and contrasted in this paper, along with an introduction to the application of Diamond as a single-photon source and the other promising quantum applications that nitrogen vacancy centres in Diamond offer.

This paper's contributing effort is to present the developments in quantum cryptology from a fundamental approach without the complexities and proofs that normally accompany reports of this nature. The purpose is to provide those interested in past, present, and future developments in QKD with an initial source from which further knowledge and/or applicable research can be pursued. Proofs are referenced, when necessary, in order to facilitate this effort. The paper begins with a basic introduction to 'Quantum Theory' to familiarize the reader with some of the terms, concepts, and theories that may be encountered in subsequent papers or research. The report then surveys the various quantum encoding technologies implemented in the SECOQC QKD network to compare and contrast these schemes and concludes with a discussion on Diamond and the impact and future promise this technology offers to the world of QKD.

2. QUANTUM THEORY: AN INTRODUCTION

Quantum mechanics is the study of systems on a microscopic scale. It began as a science in the twentieth century as a branch of physics when it became clear "that classical physics led to predictions in disagreement with experiment" [1] (p.49). Heisenberg's uncertainty principle [1] (p.84) is the theoretical foundation of quantum mechanics which required a new mathematical model to explain the contradictions in classical physics: the wave-particle duality of light is one good example.

In order to view states of a system, it is necessary to identify where this quantum state exists in an infinite-dimensioned vector space. A Qubit, quantum bit, is the resultant unit entity.

Figure 1.1 illustrates the location of two 'basis' systems in which the vector ψ exists and can be defined by four unit vectors R1, R2, horizontal/vertical 'rectilinear basis' and ϴD1, ØD2, 45 degree/135 degree 'diagonal basis'. The two 'bases' are said to be conjugate, equal length vector projections of the other basis [3], and exist in the same vector space. Therefore, according to Heisenberg, measuring one basis vector causes the system to collapse and lose all other states. It is these bases that form the principle for the polarization of a photon, a 'qubit of light', initially introduced in 1984 by Bennett and Brassard [3] and herein referred to as the BB84 protocol.

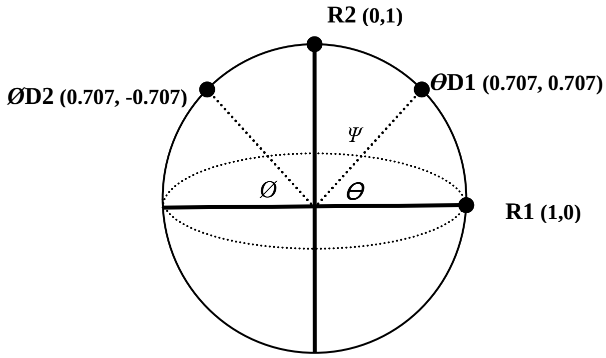

Figure 1.1 Two Basis Systems.
Vector ψ can be defined by four unit vectors, R1, R2 horizontal/vertical 'rectilinear' basis and ϴD1, ØD2, 45 degree/135 degree 'diagonal' basis.

Figures 1.2 through 1.6 illustrate the cryptographic algorithm described in BB84. Although several other methods have been developed [1] (p.202) [7, 8] since BB84, the model for the polarization of photons remains consistent. Photons are emitted in all directions of the vector space when they leave a light source. For cryptography, only two 'bases' are required, the rectilinear R1- R2 axis and diagonal conjugate ϴD1- ØD2, as depicted in Figure 1.1. A polarization filter of the ✚ type will allow horizontal photons from the R1 rectilinear basis through and filter out the vertical R2 photons. A filter of the ✖ type will allow photons from the ØD2 diagonal basis through and filter out the 45 degree ϴD1 photons. It is important to note that the ✚ filter has a 50 percent chance of counting photons from either diagonal basis and that, conversely, the ✖ filter has a 50 percent chance of counting photons from the rectilinear basis. The resultant encoding scheme is interpreted in Table 1.

Table 1. Resultant Encoding Scheme.

Orientation	Binary Value
↔ ⤢	0
↕ ⤡	1

In Figure 1.2, Sender A, Alice, generates a string of photons to send to Bob, Receiver B, over a quantum link. Alice remembers the photons' filter orientation as she sends the photons. Bob chooses his polarizing ✚ ✖ filters at random and records the results.

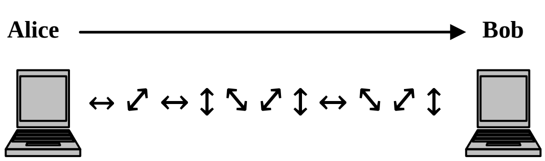

Figure 1.2 Transmissions of Photons by user Alice.
Adapted from [13] (pp. 774-778)

The ✚ filters chosen will accurately distinguish between ↔ ↕ photons, but may also indicate false positives on the ⤡ ⤢. The ✖ filter will accurately distinguish between ⤡ ⤢ photons, but may also indicate false positives on the ↔ ↕ photons. The results are interpreted in Figure 1.3.

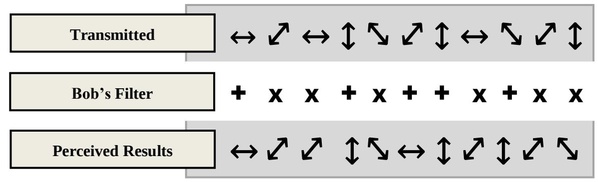

Figure 1.3 Perceived Results by User Bob.
Adapted from [13] (pp. 774-778)

Some of the results are true and some of the results are not. When Bob measures a photon, all other information regarding the photon's 'basis' and its conjugate is lost, so only half of the communication channel has carried any meaningful data and only the data where the proper polarisation filter was chosen is recovered correctly. In this case, six photons are detected correctly, as indicated in Figure 1.4, but Bob is still unaware of this.

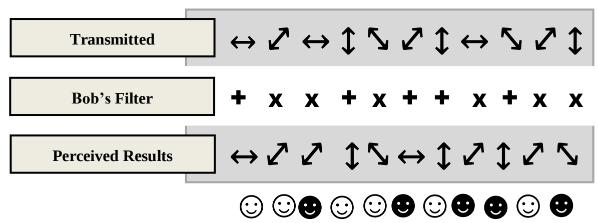

Figure 1.4 Detected Photons.
Adapted from [13] (pp. 774-778)

Bob now contacts Alice on a public communication channel and tells her what filters he used. As indicated in Figure 1.5.

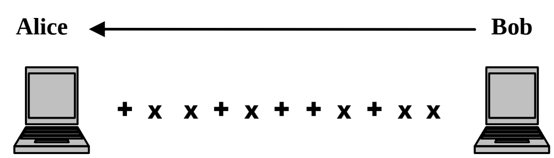

Figure 1.5 Filters Used by Bob.
Adapted from [13] (pp. 774-778)

In Figure 1.6, Alice calls Bob back and tells him which filters were correct.

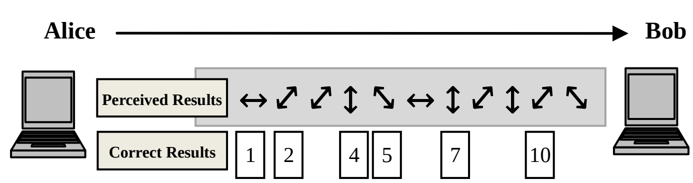

Figure 1.6 Correct Filters.
Adapted from [13] (pp. 774-778)

Bob can now convert the photons into binary bits with the understanding that ↔ ⤢ = binary **0** and ↕ ⤡ = a binary **1** as indicated in Table 1. The results are shown in Figure 1.7

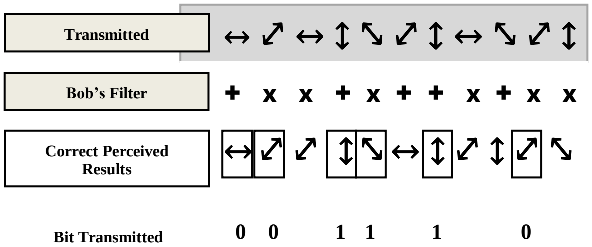

Figure 1.7 Correct Results.
Adapted from [13] (pp. 774-778)

In Figure 1.7, the resulting string from this communication session can now be used as an encryption key for data transfer over a public network. It is important to note that this protocol effectively distributes a one-time pad (OTP), the only known secure scheme, according to Classical Information Security Theory, that cannot be subjected to attacks based on computational power. It is also important to note that, with this protocol, Bob can tell Alice which filters he used and Alice can tell Bob which ones will yield the correct results over a public channel without actually revealing anything about the data initially sent over the quantum link. Furthermore, any eavesdropper on the quantum link will perturb the information exchange according to Heisenberg's Uncertainty Principle and Bob and Alice could determine this intrusion because of the excessive amount of incorrect results being experienced on the link [3].

Before concluding this discussion on the micro-world of the quantum and returning to the macro-world of classical physics, there a few more concepts which need to be discussed, namely, decoherence and entangled quantum states. Decoherence, which is a loss of quantum coherence [2] (p.335), is the term used when quantum data is coupled to the classical world of physics. This coupling causes a corruption of the data, according to Heisenberg, and effectively rules out the ability to clone a qubit, also known as the 'no-cloning theorem' [1] (p.194). If qubits cannot be stored and retrieved, this presents a major obstacle when it comes to designing the classical repeaters and switches necessary to overcome propagation losses in QBB fiber segments. This issue will be addressed further in the discussion of Diamond.

The Einstein, Podolsky, Rosen paradox [1] (p.88), herein referred to as EPR, is the result of a scientific paper introduced in 1935 by Einstein et al, investigating the counter-intuitive properties of quantum mechanics, namely, the phenomenon of entanglement in quantum systems. According to the entanglement theory, it is possible for one particle to interact with another particle in such a way that the quantum states of the two particles form a single entangled state, creating a dependency. Because of this dependency, they can no longer be considered as separate states, even if their individual localities change. The EPR objection to quantum theory was based on two tenets. The first tenet is the denial of physical reality before observation. Quantum theory states that a particle gains physical reality only after it is measured and that, before it is measured, it is considered to be in a superposition state where it exists and does not exist. The second tenet is the violation of the principle of locality by entangled dependency [1] (p.89). It took thirty years before the mathematical proofs of physicist John Bell validated quantum entanglements. It took an additional twenty-five years before experiments like the one conducted in Rome in 1998 by Boschi et al [2] (p.581) were successful in the teleportation of an entangled pair of photons. The theoretical state of entanglement, often referred to as an EPR or Bell state, is now the 'basis' for several QKD communication protocols. The University of Vienna implementation in the SECOQC network discussed in the following section is one such protocol.

3. SECOQC QKD

SECOQC is a European Union Frame Work 6 (FP6) integrated project funded by the European commission in 2004 under its Future and Emerging Technologies (FET) initiative [18]. The aim of this research was to investigate and develop quantum cryptography technologies with standardization as an eventual outcome through the Industry Specification Group (ISG) of the European Telecommunications Standards Institute (ETSI).

Figure 2.1 illustrates a four node configuration of the network developed to facilitate this research. Each node is connected to the network via a public communications channel, a private quantum channel and a Quantum Point-to-Point Protocol (Q3P) logical device association connection. For fault tolerance and efficient key distribution, the QBB links are connected in a full mesh topology.

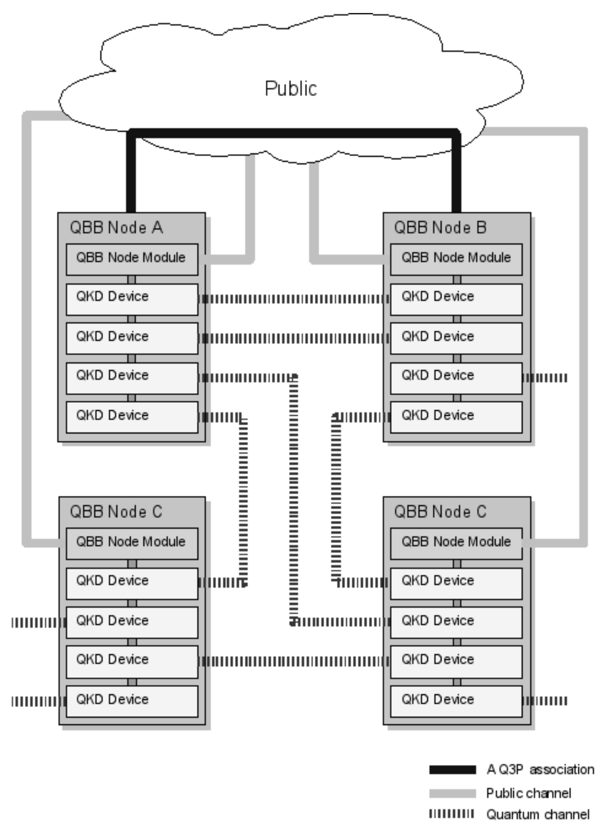

Figure 2.1 Four Node QBB
Four nodes of a QBB are connected via quantum channels and communicate over the public channels. Between nodes A and B, one specific connection is highlighted to emphasize the communication of the Q3P network protocol.
Adapted from [14] (p.6)

3.1 SECOQC QKD-Link-devices

One of the implementation requirements of SECOQC network deployed in Vienna was to ensure inter-operability at the datalink layer for any developed QKD technology. In order to gain a broader understanding of the current QKD technologies available, this section will describe, contrast and compare the currently supported link layer devices in the SECOQC network.

3.1.1 Phase Shifting Interferometer [4, 7, 12]

Qubits are encoded by phase shifting of photons instead of polarization whereby short/long interfering photon pulses are input into the same media, resulting in either constructive or destructive wave interference. Mirrors are used to offset the effects of birefringence, which is the separation of a beam of light into two rays as it passes through a fiber medium. Birefringence creates different velocities of the polarized components and results in the change of their polarization state. Figure 2.2.1 illustrates the encoding process.

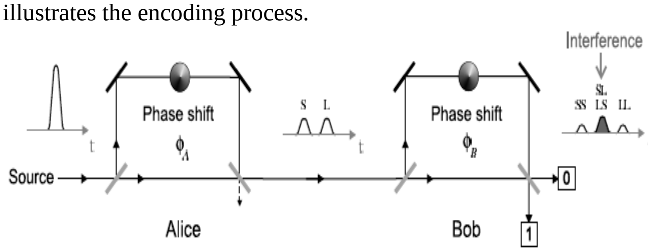

Figure 2.2.1 Phase-encoded QKD with a double interferometer. *See text for details.*
Adapted from [7] (p.20).

In Figure 2.2.1, Alice controls the phase shift in the φA arm of the interferometer. Bob controls the phase shift in the φB arm. If Alice's and Bob's phase shifts are the same or differ by 180◦, then Bob will detect constructive interference (long path/short path, LS or short path/long path, SL) in one of the outputs and destructive interference in the other (short path/short path, SS or long path/long path, LL). If the total phase shift between the arms is different by a multiple of 180◦, photons will be detected at both detectors. The encoding scheme used is similar to the BB84 scheme and is outlined in B92 [4]. Refer to Figure 2.2.2, Encoding Scheme.

ϕ_A	$+$:	$0^\circ \ldots$ "1",	$180^\circ \ldots$ "0"	ϕ_B	$+$:	0°
	$\times$:	$90^\circ \ldots$ "1",	$270^\circ \ldots$ "0"		$\times$:	90°

Figure 2.2.2 Encoding Scheme. *See text for details.*
Adapted from [7] (p.20).

In Figure 2.2.2 Alice encodes qubits into four quantum states by sending weak light pulses to the interferometer and sets a random phase for φA to 0◦, 90◦, 180◦, or 270◦. Bobs sets a random phase φB to 0◦ or 90◦. These values correspond to the measurement in the "rectilinear" and "diagonal" bases, of the BB84 protocol.

This form of QKD was shown to generate approximately 300 photons per second and reliably distribute them over 23km fiber segment [12] using 1300nm single-mode fiber channel.

3.1.2 Weak Coherent Pulses [21]

Attenuated light pulses carry qubit pairs in one of three states. See Figure 2.3. Coherence between the photon pairs will reveal any intruder trying to extract in band information.

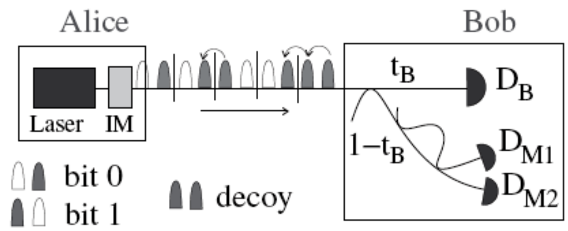

Figure 2.3 Weak Coherent Pulsed QKD. *See text for details.*
Adapted from [21]

In Figure 2.3, Pulses with arrows over them indicate a coherence created by the intensity modulator (IM), which either prepares a number of bits for transmission or completely blocks them out. The bits are encoded into two-pulse sequences consisting of an empty pulse and a non-empty pulse corresponding to bit 0 or bit 1. Alice sends a large number of random bit 0, bit 1, and decoy sequences. At the end of the exchange, Bob reveals which were detected on the data line Db and when detector DM2 has fired. Alice tells Bob which bits to remove from his raw key, since they are decoy detections. The pulses that are reflected at Bob's beam-splitter at 1-tb go to the interferometer to check quantum coherence. When both pulses are non-empty, only detector DM1 can fire. The probability that detector DM2 fired when only DM1 should have fired can be easily calculated by Alice to estimate the de-coherence associated with the 1-0 bit sequences and the decoy sequences, indicating that an intrusion occurred. This form of QKD is not sensitive to the polarization effects of the fiber optic media and is capable of high transmission rates of keys in 1550nm wave length. Key generation is restricted only by the limitations of the detection technology currently available and the system's ability to produce photons rapidly [12]. Fiber optic segment length is currently limited by the line loss properties of the standard telecom single-mode fibers available. Line loss for 1300nm wave length is approximately .35dB/km and .20dB/km for 1550nm [7] (p.33). At .20dB/km, this would translate to 99% loss after 100km [7].

3.1.3 Entangled photons, University of Vienna [10]

Entanglements of photons can be of different natures. For example, a photon pair can be entangled on the rectilinear basis. If one photon is polarised at the horizontal vector, the other would automatically be at the vertical. Conversely, if the diagonal basis is used, one photon is polarised on the 45 degrees axis, while the other will be on 135 degree axis. Only one photon of the entangled pair needs to be measured directly, as the state of the other photon can be determined due to the quantum nature of entanglements. For this reason, quantum communication is possible even if the measurements are not performed at the same time. Figure 3.1 illustrates a Spontaneous Parametric Down-Conversion (SPDC) [10] method which generates an asymmetric photon pair at 810nm and 1550nm wave lengths.

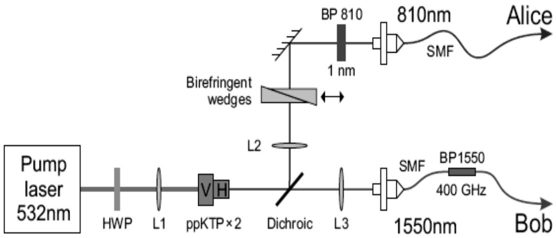

Figure 3.1 Spontaneous Parametric Down-Conversion Entanglement QKD. *See text for details.* Adapted from [10]

In Figure 3.1 a solid state diode 532nm laser is focused on (L1) at the edge of the two Potassium Titanyl Phosphate (KTP) crystals for down-conversion. The half-wave-plate (HWP) rotates the pump to excite the horizontal (H) and vertical (V) crystals equally. The 810nm and 1550nm photons are separated by a beam splitter (Dichroic) and refocused by lens L2 and L3 and then coupled into single-mode fibers (SMF). The photons are further processed using BP 1550 and BP 810 filters. The birefringent wedges in the 810nm arm are to compensate for timing offsets between the entangled photons [10]. Encoding is accomplished according to the BBM92 [5] protocol for entangled photons. This form of QKD was shown to distribute 100 pairs/sec. of entangled photons over 100km fiber segment using 1550nm single mode fiber [10].

3.1.4 Free-space System [17]

This technology utilises weak coherence pulses transmitted over the air at a distance of 144km and to distribute keys at a rate of approximately 12.8 bit/sec. [17]. Figure 4.1 illustrates the system.

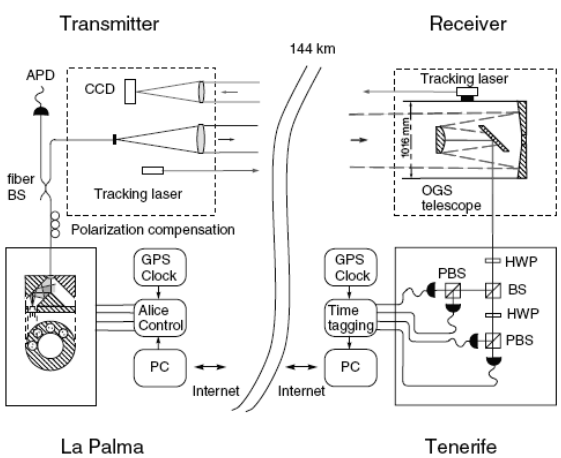

Figure 4.1 Free-space Experimental System. *See text for details.* Adapted from [17] (p.2)

In Figure 4.1, BS beam splitter, PBS polarizing beam splitter; HWP half-wave plates, APD avalanche photo diode, comprise the main Free Space system components. An optical pulse centred at 850nm is emitted according to random bit values, generated by a random number generator stored on Alice's hard disk. Four output beams are generated and coupled into a single mode optical fiber running to the transmitter telescope. Photons are then sent through the atmosphere to the receiving telescope to be decoded. Decoy pulses are randomly interspersed in the signal sequence by firing two randomly chosen diodes simultaneously. The encoding process is similar to that described in Figure 2.3 [17]. Using the 860nm optical range permits the usage of efficient low-noise semi-conductor devices which could not be used in optical fiber systems simply because optical fibers are not manufactured in this wave length [7] (p.33). The atmosphere has a low absorption rate at 770nm and 860nm wave lengths, and does not introduce any birefringent loss. Consequently, free-space systems can achieve longer transmission lengths. This opens up the possibility to use low earth satellite systems to create a truly global quantum key distribution system; however, the atmosphere is susceptible to changes in weather conditions and signal loss could reach as high as 20 dB in heavy mist conditions [7] (p.33).

3.1.5 QKD Technology Summary

Table 2 summarises the QKD technologies surveyed and compares their abilities based on Rapidity, the rate at which keys can be affectively distributed and their Reliability. Free-space systems offer promise as a global solution but current technologies have a low rapidity rate and their reliability is dependent on stable atmospheric conditions. Entangled photon pairs provide a ten fold improvement in the rapidity rate over the free-space system but current single mode fiber technologies restrict reliable segment lengths to 100km or less. Entanglements over free-space are possible but would still be subject to atmospheric disturbances. Phase shifting interferometer has a three fold improvement over current entanglement technology but reliability is limited to a maximum of 23km fiber segments. Weak coherent pulses offer the highest rapidity rates but reliability is restricted to the current fiber technology limitations.

Table 2. Technology Summary

Quantum Key Distribution Technologies		
Encoding Method	**Rapidity**	**Reliability**
Phase Shifting Interferometer	≤300 photons/sec. at 1300nm	≤23km single-mode fiber Suppresses birefringence
Weak Coherent Pulses	Limited to the number photons the system can generate and detect at pulse time. Current technologies detect up to 17,000 photons/sec.	Not sensitive to the polarization effects of birefringence <100km 1550nm single-mode fiber
Entangled Photons	≤100 entangled pairs/sec.	Theoretical distance is unlimited. Current technologies only allow ≤ 100km with 1550nm single-mode fiber
Free-space Systems	12.8 photons/sec.	≤ 144km 850nm Not sensitive to the polarization effects of birefringence. Susceptible to changes in weather

4. DIAMOND

The SECOQC network and the technologies discussed to this point are applied proofs of the theoretical models of quantum physics. Still, there is scepticism that QKD is a viable solution for the current 'Classical Public-Key and Key Establishment' which relies on computational difficulty as a deterrent from brute force attack when long keys are used.

The objections to QKD are often centred on the principles of quantum physics like decoherence and the 'no-cloning theorem', both of which prevent the storage and retrieval of quantum states. Thus limiting the usefulness of such networks to niche markets, since propagation losses in QBB fiber segments, coupled with the inability to store and forward messages, rule out QBB networks in a global scope.

Another objection is the low rapidity rate for the generation of keys which is chiefly limited by the inability to produce and control low cost single photons. However, recent experiments in photon coupling via microwave cavities, also called cavity quantum electrodynamics (QED), have once again revolutionised quantum mechanics with demonstrations of quantum memory and quantum bus facilities.

In 2007, two experiments effectively nullified the preceding two objections. Firstly, Hijlkem et al produced a "single-photon server with just one atom" [9], capable of delivering 300,000 photons for a 30 second interval and, secondly, that same year Sillanpaa et al successfully stored several quantum bits in a QED and retrieved an individual qubit from the same QED [20].

Given the recent developments in Diamond research, it appears that the sceptics will soon have to re-think their arguments. After several years of research [15, 16, 22, 23], Dr. James Rabeau and the Quantum Materials and Applications (QMApp) group at Macquarie University at Sydney, Australia, have succeeded in creating a reliable "solid-state triggered single-photon source" [23] (p.1) capable of delivering photons on demand at room temperatures. The process involves the use of "high-pressure high-temperature (HPHT) grown diamond samples where nickel is used as a solvent/catalyst for the HPHT crystal growth" [23] (p.1) and nitrogen impurities are subsequently added to create a nickel-nitrogen colour centre with an emission band in the 800nm spectrum. This process, called chemical vapour deposition (CVD), can be controlled to create nano-diamonds with nickel-nitrogen centres which can be grown on optical fiber ends or QED resonance chambers. Diamond's unique spectral properties are also being investigated for its store-forward and memory capabilities for use in network repeaters and quantum computing memories [6, 11].

5. CONCLUSION

The impacts on network security and the management of homogenous networks that current and future developments in quantum will create are in a state of superposition where they exist and, at the same time, do not exist. The SECOQC network and technologies implemented and reviewed in this paper are a first step in preparing for the eventual leap to the decoherence that quantum networks will bring. Further steps will require the promotion and establishment of international standards and it appears that SECOQC is also a front runner in this regard [18].

To conclude, this document has provided a brief history of the 'Quantum' and the technology that has evolved the current state of the art. The approach has been relatively simplistic compared to the complexities of quantum mechanics. For readers who require an in-depth look into quantum, the Benenti texts [1, 2] referenced in this paper are an excellent source and contain the mathematical proofs for many of the theoretical models presented.

6. ACKNOWLEDGMENT

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