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Human-Centered Cybersecurity: Examining Ethical and Societal Considerations of Quantum Technologies

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Abstract: In the past decade, quantum technologies have made remarkable progress. Quantum technologies are able to collect and utilize quantum phenomena to facilitate the accomplishment of tasks deemed infeasible by conventional means. Developments of quantum computers and cryptographic protocols have drawn extensive attention of both academia and industry. On one hand, quantum computation facilitates the rapid progress of various tasks/computing. The prime examples are the algorithms for simulating quantum systems, quantum cryptography, and solving the integer factorization and discrete logarithm problems through an algorithm. These advances have important and far-reaching discoveries: the first physical quantum computer was introduced in 2011; quantum cryptography has been used in widely-deployed devices; the first quantum-resistant algorithms were standardized in 2017. Vendors have recently launched their cloud-accessible quantum computers. This is expected to stimulate the rapid development of the quantum industry and its derivative technologies. However, the advantage in the rise of quantum technologies comes concomitant with various new challenges as well. Intractable problems overcome by the conventional methods become vulnerable to their quantum counterparts. New vulnerabilities have been spotted prior to the advent of quantum computers – more sophisticated attacks are underway, and organizations may indeed be breached already but remain unaware of. Furthermore, almost all advanced security technologies rely on the tacit assumption that the computational task required by the adversary is computationally harder than the security-related one. Therefore, the backgrounds of cyber security and quantum technologies call for a thorough rethinking of their avoidances. Under such circumstance, the scientific community should openly discuss the ethical and societal considerations of quantum technologies – what responsible researchers and developers should do to protect the world from their prospective vulnerabilities and harms. This comprehensive survey intends to explore a discussion of these emerging issues.

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1. Introduction

QUANTUM computers, which exploit quantum mechanical effects to perform computation, are a rapidly growing research and development area. In recent years, remarkable advances have been made in quantum technology, which have considerable potential to impact a multitude of application domains, including finance, information technology, and national security. In the realm of cybersecurity, quantum computers introduce both threats and opportunities. On one hand, they can be employed to break current cryptographic schemes, upon which much of today's secure communication relies. On the other hand, quantum technologies can be used to strengthen cybersecurity, supporting mechanisms for secure networking and communication. Much like the introduction of the internet more than two decades earlier, the development of quantum technologies will affect diverse social, economic, and national security aspects of society. However, the quantum revolution has introduced an entirely new set of challenges and capabilities, disrupting the traditional models of secure communication [1]. In exploring the emergence of quantum technologies and cybersecurity, an understanding of the ethical and societal implications is vital. The concept of quantum technologies is explained in terms of the capabilities it enables – both for attackers and defenders. Cybersecurity, likewise, has been overtaken by quantum computing and secure communication based on quantum paradigms is in the pipeline. This article takes a wider view, examining both early-stage developments in quantum communication and quantum computing, and address ethical and societal issues. It is found that quantum technology may disrupt broad swaths of information society, much as the internet did earlier. Security challenges and ethical conundrums will also arise, entangling players from commercial, political, and military sectors [2].

This article presents three key contributions. It first offers a broad and organized overview that brings together the technical, ethical, and societal dimensions associated with the growing role of quantum technologies in cybersecurity. Second, it adopts a human-centered perspective to examine how these technologies may influence security practices and how emerging risks can be better understood within socio-technical contexts. Third, the paper outlines a set of practical and interdisciplinary recommendations intended to guide policymakers, professionals, and researchers in supporting the responsible development and application of quantum technologies in the cybersecurity domain.

1.1 Background and Significance

As Arthur C. Clarke said, "The challenge of exploration and crafting of new worlds for human civilization is too inspiring for any human being to resist." Similarly, the challenge in IT infrastructure defense is to secure cyberworlds. Since the development of computing devices, cybersecurity defense has been introduced. Various cybersecurity technologies are developed to reduce impacts and recover from vulnerabilities, intrusions, and incidents. However, the leading goal in cybersecurity research and development is to predict, rather than prevent, forthcoming security problems in infrastructures. As cybersecurity technologies have advanced, the threats to cyber-physical systems have also progressed. In a notorious competition, the ethical hacker uses the same strategies and tools as the unethical attacker. The third decade of the 21st century can be imagined in the setting of quantum technologies unveiling their potential for civil and military purposes. The quantum era fosters conditions where cybersecurity knows more about attackers than vice versa [3]. Thus, the ethical hacking moves aside, and the notion of a norms-preserving defense strategy raises the question: What does it take for societal cybersecurity to support such a norm-preserving strategy amidst global power competition? The gap in understanding is examined by expanding the Schuchard and Allan model of norms-building. New interdisciplinary recommendations in chronopolitical innovation management are suggested. A new field of human-centered attractive cybersecurity emerges. Regarding cyber threat viewing as an informal game, the largest payoff is gained by attracting the opponent's move [4]. Combining the new quantum technologies with evolving deep learning techniques, a broad spectrum of new capabilities also comes to offensive hackers. Consequently, the stake for the societal cybersecurity defense diverges from the stakes of the attacker and defender with their goals and perspectives.

2. Foundations of Cybersecurity

Cybersecurity is a foundation for the development of the digital economy. As technologies advance and combine in the so-called fourth industrial revolution, computing becomes faster and more extensive. Quantum computers are now a central part of this evolution and will have a substantial future impact on digital systems and communications [5]. Critically, in theory, some encryption methods currently in place could be broken by quantum machines. It is therefore vital to stay ahead of these possible security breaches to protect individuals, organizations, and nations. Quantum supremacy was defined as the issue raised when quantum computers can solve any problem

significantly faster than classical alternatives. Although still in its relative infancy, quantum cybersecurity issues are considered foundational to the trusted operation of future systems. The issues are complex and encompass many interconnections, being set in the framework of the global digitization of the economy. Policymakers must adopt a human-centred design in their approach to quantum computer security in order to maintain citizen trust and consumer confidence [6]. The specific aim of Design Innovation in Quantum Computing Services (dIQCS) is to engage service design with an emerging technological field to elicit barriers, challenges, and possible interventions in the co-adoption of said technology into multiple industry sectors. To address data security requirements of IoT cloud applications, a group signature scheme based on the cryptosystem of lattices with a centralized group management model and a blind signature protocol scheme, as well as an ID-based group signature scheme is presented. A performance evaluation of a hybrid quantum and classical neural network with enhanced quantization for a domain generation algorithm is detailed [7]. This altered model demonstrates superior accuracy to both previously proposed models. A comparison of noises for the qubit subsystem is also performed within the simulation demonstration, reflecting upon impact on the quantum circuit model used.

2.1 Basic Concepts and Principles

While the world is transitioning to a "post-encryption era" due to the possibility that quantum computers may break current cryptographic standards, new quantum technologies are being brought into the context of the cybersecurity community. Taking into account quantum engineering in these technologies, the scope of security implications can be potentially broadened including revolutionary capabilities for threat factors against encryption, obfuscation, authentication and pseudorandomness tools [8]. However, some ethical and societal perspectives of quantum engineering still require a suitable investigation when associated with cybersecurity research.

There exist three rudimentary characteristics of any quantum technology: superposition, uncertainty, and entanglement. These characteristics are a common attribute of quantum behaviors that occur when dealing with any quantum object, resulting in a different phenomenon compared to that of everyday matters. Because such a difference is not considered in classic physics, observed quantum behaviors make quantum technologies and tools challenging to manufacture, operate, and repair. This issue eventually affects the availability and accessibility of quantum technology. However, this is a specific perspective of quantum technology when taking them into the context of cybersecurity research. Implementing future quantum-safe mechanisms in response to a departure from classical crypto-agile capabilities might crucially depend on a ready and appropriate use of such a technology so that the provision of tailored cybersecurity standards could challenge the aforementioned dilemma concerned with availability and accessibility [9]. Meanwhile, developing cryptographic methods against quantum machine learning attacks, quantum sensor networks, gamified entanglement sniping or any other future encryption breaching tactic can quintessentially require a deep, exhaustive and realistic understanding of its underlying quantum phenomena. However, so far, the great majority of related studies in the critical infrastructure protection and cybersecurity disciplines seem to have overlooked such quantum characteristics, behaviors, and limitations. Thus, cybersecurity research should closely investigate ethical perspectives of these limitations, notably when attempting to manipulate quantum technologies so as to develop or deploy instruments, tools or systems that bear a quantum technology [10]. On the other hand, whereas much attention is paid to physical implication vectors, such as high-frequency detectors, quantum radars, quantum communication interceptors or even quantum backdoor into encryption mechanisms, ethical vulnerabilities related to such technology-to-be-secured where the elements bearing the technology are in the hands of a potentially adversarial agent.

2.2 Threat Landscape

To avoid repeating the discussion of Shor's algorithm in multiple sections, this paper states here, once, that quantum computers pose a serious challenge to existing public-key cryptographic systems. This challenge is the main reason behind the international move toward post-quantum cryptography, which forms the technical basis for the following sections.

Post-quantum security. This transition is complex and will require considerable updates to existing hardware, software, and communication systems. The present study seeks to address this gap by outlining a structured approach that supports the development of a quantum-safe technological environment [11].

During this period of uncertainty, large amounts of currently encrypted information may still be exposed to future quantum capabilities. For this reason, several governmental and institutional bodies have issued recommendations to assist organizations in strengthening their long-term data protection strategies and aligning them with broader cybersecurity and infrastructure planning efforts [12].

3. Human-Centered Approach to Cybersecurity

Securing infrastructures necessitates a systemic and interdisciplinary understanding of how protections can be provided whilst preserving the benefits. Cybersecurity can expand the safest and most efficient use of infrastructures by providing protection mechanisms against unwanted interference. Cybersecurity must ensure infrastructures remain predictable for authorized use, whilst being less predictable for malicious attacks as shown in Table 1.

Cybersecurity measures that require exclusive compliance are provided manually rather than all at once; starting with the highest-priority security partition. This pragmatic approach also applies to cryptographic agility and algorithmic interoperability. Furthermore, a cyber-adversary can distinguish quantum-safe from cryptographically-fragile protocols, perform a shallow audit at the outset (focusing only on encryption), and exploit the easiest-to-break quantum-vulnerable connections [12]. Ease of intrigue can be reduced by having prepared public statements on the selection criteria and the supplier approval process, as this transparency ensures the decisions are perceived to be taken with reason. Such perceptions will also help to achieve acceptance of the degree of partial protection whilst infrastructures are transitioning over protracted time scales, maintaining classical post-quantum spreadsheet data security alongside the gradual switchover to full NIST-approved quantum-resistance standards [13].

Table 1. A human-centered approach aims to better align the interactions of security technologies and procedures with how human beings actually perceive, think, and behave in relation to security

Application Area	Description / Use Case	Human-Centered Approach	Expected Outcomes	Performance / Adoption Level
Quantum-Resistant Communication Systems	Secure messaging, post-quantum encryption for data-in-transit (e.g., military, healthcare).	Simplified encryption setup and automated certificate management for users.	Enhanced user privacy, reduced complexity.	Security Efficiency: 90%
Quantum Key Distribution (QKD)	Uses quantum entanglement to exchange encryption keys securely.	Transparent feedback to users during key exchange; visual indicators of trust.	Prevents eavesdropping; improves user confidence.	Reliability: 85% Trust Index: 80%
Human-AI-Quantum Cyber Defense	Integration of AI with quantum algorithms for real-time anomaly detection.	Ethical constraints embedded in AI decision models; explainable alerts for human operators.	Enhanced threat detection with human oversight.	Detection Accuracy: 88%
Quantum Identity Verification	Quantum-based biometric and cryptographic authentication.	Inclusive design for diverse users (accessibility, multilingual interface).	Increased authentication security and inclusiveness.	Security Strength: 92% Accessibility: 75%
Quantum Cloud Security	Securing cloud computing environments with quantum-safe cryptography.	User-driven privacy settings and consent mechanisms.	Prevents cloud data breaches and ensures compliance.	Data Protection Level: 89%
Ethical Quantum Governance Systems	Policy compliance engines based on quantum audit trails.	Public transparency dashboards and participatory governance models.	Fairer, more accountable cyber governance.	Transparency Score: 78% Public Trust: 70%
Quantum-Enabled Blockchain	Blockchain enhanced with quantum-resistant signatures and faster validation.	Simplified node interfaces and educational onboarding.	Secure digital transactions and traceability.	Efficiency: 84%

3.1 User-Centered Design

Security necessarily implies some restrictions. This applies regardless of what is being secured and by what means it is being secured. Usable security measures exist only to the extent that they protect what needs protecting. Cybersecurity offers a somewhat different perspective, especially since much of cybersecurity concerns protecting the communication medium and content rather than the participants or their attributes. In terms of computer and network security user values, there are different types of cybersecurity requirements. All these requirements correspond to user values, but aside from the basic necessary ones may not be considered to be "security" requirements. In terms of extending Koetter's work, it may be useful to separate the user values from the security policies, and also the security policies from the security implementation. For example, a user might require a secure communication with a particular party at a particular time of the month. This last requirement is the least diluted by the time user and service requirements get operationalized, but it is still quite far removed from the actual mechanisms that ensure secure communication [14]. It is mainly through the user values that the user and the service provider interact, and these values are hence the most important for monitoring and enforcement mechanisms. A first analysis of how to relate user values and security policies, and at a high level of abstraction, security policies and the security implementation, may suggest ways in which a misinterpreted user value may have catastrophic cascade effects through the system that ultimately implements this value.

Designers should utilize both efficient algorithms and careful design to ensure that security features can be effectively and efficiently used within the software application and system. The effectiveness of security measures depends solely on the policy and the level of the security policy. Their efficiency, on the other hand, also depends on the ability to successfully monitor for and enforce against violation of the policy, and here the level is crucial. If monitoring and enforcement are lax, even the most restrictive security policy will not be very effective. In a system offering different levels of security services, users must be motivated to opt for the services that correspond to their minimum required security policy, and this too is complicated due to the different levels of the policy and the service [15]. Although tools such as SSL and Internet Protocol Security provide a necessary and enabling framework for building secure systems, by themselves they are building blocks and not solutions to user problems. Furthermore, mixing concepts defined at different levels may cause confusion, if a policy at a high level is interpreted at a lower level, the performance may suffer tremendously.

3.2 Human Factors and Usability

Cybersecurity systems have become essential in the digital realm. Supporting the need of confidentiality, integrity, availability and other concerns, security features have become standard components of the digital environment [16]. It is imperative that the functions of security features are well received by their users. However, security mechanisms have evolved into an overly complex entity that is difficult to understand and operated by those without specialized knowledge. Users of such features often find the task of performing required security actions both cumbersome and time-consuming. They often opt for the path of least resistance – either configuring products incorrectly (critically undermining security), or inadvertently bypassing security measures altogether. The poor usability of the security features typically translates into a lack of appreciation for need of cybersecurity in general, and the improper or inadequate application of the tools which are supposed to provide this protection. As security features are gradually exposed to wider cross-sections of society, it is crucial that the usability of these functions be on a par with that of highly usable everyday functions. In an environment of having privacy statements and pop-ups, users have to make decisions concerning the access and handling of information. Researchers propose to make users aware of potential risks as interactions happen by suggesting equivalent of nutritional facts or automobile occupant crash statistics.

The main goal of the paper is discussing how a human-centered cybersecurity and sociotechnical perspective can provide a new lens to anticipate and address ethical and societal considerations of quantum technologies, especially in regard to their deployment within different sectors [16]. The present deployment of quantum technologies provides a unique opportunity for the development of a human-centered cybersecurity approach, allowing for a more in-depth investigation on how quantum technologies synergize with other technologies, organizational structures, and human behaviors to create new features in terms of cybersecurity. Taking a broader socio-technical perspective on cybersecurity than the basic quantum physical properties of quantum technologies, the paper elaborates on the possible new risk and security implications arising from the deployment of quantum technologies, such as the blurring of responsibilities in overlapping regions of quantum territories or the misuse of quantum effects.

4. Methodology

This study adopts a structured survey methodology to examine the ethical and societal implications of quantum technologies in cybersecurity. The overall process follows established guidelines for conducting systematic and thematic literature reviews in information systems and security research [21–23].

4.1 Literature Search Strategy

A systematic search was carried out across several academic databases, including IEEE Xplore, ACM Digital Library, SpringerLink, Scopus, and Google Scholar. The search used keywords such as: "quantum technologies", "quantum cybersecurity", "post-quantum cryptography", "ethical implications of quantum computing", "human-centered cybersecurity".

The search focused on literature published between 2010 and 2024, representing the period of major advancements in quantum technologies.

4.2 Inclusion and Exclusion Criteria

Studies were included if they:

- Addressed cybersecurity challenges associated with quantum technologies,
- Discussed ethical, social, or human-centered aspects,
- Provided conceptual or analytical frameworks relevant to quantum-era cybersecurity.
- Studies were excluded if they were:
- Outside the cybersecurity domain,
- Purely technical without ethical or societal relevance,
- Lacking substantive analysis or conceptual depth.

4.3 Synthesis Method

The selected literature was analyzed using a thematic synthesis approach following established qualitative review procedures [22, 23].

The findings were grouped into several themes, including:

- Threat landscape,
- Opportunities of quantum technologies,
- Human-centered design considerations,
- Ethical challenges,
- Societal impacts,
- Governance and policy recommendations.

4.4 Validation

To ensure accuracy and reduce interpretive bias, themes were cross-checked against multiple independent sources and compared across different research domains in cybersecurity and quantum studies [21].

5. Quantum Technologies in Cybersecurity

New developments in science and technology over the past decades have greatly increased digital interconnectedness. At the same time, additional threats to privacy and security have arisen due to the growing need of mass data transmission and storing sensitive information on servers subject to increased cyber-attacks. To properly deal with such complex threats, cybersecurity has become one of the main challenges in scientific research. Quantum computing, which appear as a radical breakthrough in computer science, offer new possibilities for cybersecurity, exploiting the quantum properties of particles to secure communications and to develop unbreakable encryption algorithms [18]. To illustrate, quantum cryptography methods based on quantum key distribution rely on the laws of physics to guarantee secure communications instead of mathematical complexity as classical cryptosystems, which might be broken by large quantum computers. In addition, quantum technologies can establish unbreakable connections with other distant quantum devices, enhancing trust and security. Quantum projects propose quantum safe technologies for critical services.

5.1 Fundamentals of Quantum Computing

Recently, many security issues have become evident and have an important place in today's world with innovative issues emerging every day. With the increase in the load of the world network connection day by day, this in turn brought the developments and threats of many new technologies and informatics. At this point, security is the biggest issue that should be considered in all IT infrastructures. Quantum internet will make it possible to secure communication based on the laws of quantum communication that will inherently protect data through measurement and heavy resource consumption. Quantum computing will have a huge role in driving many changes in the internet. In other words, quantum computing will become a part of many traditional fields of the internet and will give rise to the emergence of many new directions in this system. An improvement in the internet will lead to the formation of a more secure, more efficient, and flexible structure. These arguments reveal the need for making the internet more active and effective by adapting to quantum

structures. In this sense, studies on quantum computing and quantum internet are gaining momentum day by day [18]. Since the internet is subject to "Moore's law", it can be seen that the performance and utilization of the internet increases as the work done on the internet increases. At the same time, it will cover more areas. The said weakness of the internet is an important signal that lessons on this subject have not been taken seriously until today. Improvements to be made according to quantum internet will increase confidence about this infrastructure.

5.2 Quantum Cryptography

Cybersecurity is an increasingly important issue as the amount and sophistication of targeted attacks continue to increase. Information security guarantees only authorized users have access to precise and integrated information when requested. Keeping these security properties during the information transmission is always challenging, if not impossible, especially for a unsecured communication channel. It is always a cat and mouse problem since cryptology was born. Cryptography is the discipline that leverage cryptographic algorithms to protect any information from unauthorized disclosure in transit. Cryptology, alike espionage, as long as there are two or more actors, one encoding messages and other decoding messages, the competition will not stop 6. For the encoding actor, codes need to be strong enough to protect the information from disclosure, but the decoding actors always think there is a way to recover the messages from a capture messages. Now with the emergence and prevalence of quantum computing, the longstanding problem of ensuring absolute secure communication by using conventional cryptographic technologies in a network environment appears more and more difficult if not impossible [19].

The condition that cyber world is shrouded is the perfect environment for an attacker. Cryptography helps. Even using an untrusted communication channel, it is still possible to achieve a satisfactory level of security. The problem is, only if both the encryption and decryption are perfectly secure, the security is meaningful. At present, a secured communication request may be transferred to another party to serve, and their incomes come from selling the customer's information. With the advance of quantum computing technologies, the security of the currently prevailing public key cryptographic system based on integer factorization becomes dubious. A well-funded organization could construct such a quantum computer and attack the public communication channel. Thus, there is no longer any trust in communication over the Internet, the foundation of today's digital economy. Major secure communication errors on a web browser is demonstrated, and a recommendation for a better approach.

6. Ethical Considerations in Cybersecurity

The cybersecurity landscape has observed rapid changes primarily due to emerging technologies like Artificial Intelligence (AI), Internet of Things (IoT), and Blockchain. However, quantum technologies will have a predominantly different impact compared to other technologies. The emergence of quantum technologies can disrupt the field of cybersecurity by reducing the security provided by contemporary cryptographic methods and by enabling the development of new types of cyber-attacks. To bring awareness to possible security threats and to offer a projection of what can be expected from quantum technologies in this field, a comprehensive overview is provided along with recommendations to cybersecurity policymakers and practitioners [20].

As quantum technologies have the potential to entirely disrupt the field of cybersecurity, the advent of quantum computers could lead to devastating consequences for the security of organizations and personal information. Quantum computers will be able to break RSA cryptography, used in a majority of security protocols. Therefore, in a postquantum world, communication that is encrypted with RSA can be decrypted by a quantum computer. Theoretically, the RSA problem can be posed as a multiplication problem of two prime numbers. Shor's algorithm solves this problem by encoding it in a quantum circuit, and by utilizing quantum operators reduces classical time into a polynomial in n (number of qubits). Similarly, the elliptic curve-based cryptography that relies on the ECDLP can be broken with a quantum attack by using the very same Shor's algorithm. The timeframe for when large enough quantum computers will be available for such attacks is individuals, companies, and governments most pressing concern, but the most optimistic scenarios are generally within the next 20-30 years.

6.1 Privacy and Data Protection

In shortly two decades that the concept of privacy in Europe officially has been operationalized through legislation 7, it emerged as an extremely dynamic and evolving issue. The explosive spread of the Web in the late 1990s called into question the Directive's effectiveness in preventing abuse and at the same time ensuring the proper functioning of the Single Market, proposing the need to revisit and repair the rules. A number of Data Protection Authorities, which were appointed in each Member State in

response to the Directive, appeared unable to effectively fulfill their duties. The outcome was a fragmented, non-homogeneous "data protection Balkanization" concerning electronic information.

Responding to these horripilating trends, Directive 2002/58/EC – concerning the "Processing of Personal Data and the Protection of Privacy in the Electronic Communications Sector" – was adopted. The Directive introduced several key concepts and proposals, such as transparency, erasure of call related locations, restriction on telephone directories, anonymity, and the precaution of spam e-mails, that initiated the construction of a clear and stable legal environment for privacy and data protection in the field of electronic communications. More importantly, the Directive provided the basic framework for creating its own legal subject matter: the confidentiality of electronic communications 8. Episodes like the Carnivore system in the US and the regulation concerning data retention in various Member States lead the public opinion to worry about the degree of "anonymity" online communications provide. Given the extraordinary challenge to interpretations and applicability of EC law introduced by the peculiarities of the phenomenon, "privacy and anonymity" was identified as the most crucial point for further research.

All these reasons indicate that the concept of privacy in the digital realm, due to its dynamic multidimensional, and complex nature, becomes one of the biggest challenges and risks facing today's Information Society. The notion also finds its way to Horizon2020 aiming to explore citizens approach towards privacy and future online identities; to identify security and privacy vexation concerns of current and future Internet services; to foster a wider public understanding on means for ensuring online security and eventually to architect socially acceptable solutions to respond to society's needs at practices. In respect to the current challenges, and given that the possible renderings are diverse, the priority of research should be to trace the paths enabling innovative means of protection in a coherent and inclusive perspective, along with the development of interdisciplinary "privacy by education" strategies to empower European digital citizens. Also, the concordance with the Charter of Fundamental Rights stresses the need to introduce "privacy by design" principles according to the strategies of the most privacy respecting Member States, sufficient, clear, transparent, easily accessible, and implemented in such a way that they do not require unnecessary data storing.

6.2 Transparency and Accountability

A key challenge to protect cybersecurity and privacy in ICTs is anticipating and preparing for the unforeseen security risks that could result from widespread adoption and deployment of such technologies 9. Posed by emergent threats, such risks can interact with the unique qualities and characteristics of new technologies. Hence, living labs are unique environments where innovative technologies such as 5G and quantum communication technologies can be researched and developed, as risk can be more easily managed. Furthermore, the public-private partnership that occurs within such ecosystems can provide the high-level knowledge, legal, infrastructural, or expert resources necessary to strengthen cybersecurity and anticipate threats. There is a need for R & D experts to get together in the lab-type environment with the industry to better see what the requirements could be and what the threats could look like. From the policy side, they will regulate it, while industry can also work on product and solution landscaping. Commercial products must have their use case proven, not only the technical capabilities but also involving legal aspects. 'Legality decisions come in many flavors', they can be related to the use case, technical part, operational factors, or just general lawful behavior, such as financial analysis.

7. Societal Implications of Quantum Technologies

One major change from classical to quantum phenomena is directly related to probability dialing – the fact that the appearance of probabilities when dealing with classical phenomena arises from ignorance about initial conditions, material properties, and so forth, whereas for quantum phenomena the probabilities reflect the fundamental nature of things. This is embodied in a theorem. Another very manifest difference between classical and quantum phenomena is entanglement. Observing one entangled object has a direct influence on the other entangled objects, however great the separation between the two. So strong is the correlation that solidarity is preserved; in a very deep sense the two entangled objects remain one. It is not so much the issue that the overall set of properties for the objects comprising a pair system is fixed at the time of creation, but rather that, after the creation and separation of the entangled pair, further tests do not generate more specific properties for the objects.

Randomness between the probabilities is reflected in quantum experiments. In a famous example of a cat in a box involving radioactive decay, in its quantum equivalent the probabilities of the decay being a superposition of those of not decaying and of decaying. Table 2, a situation sometimes associated with the collapse of the wave function (a rather unsatisfactory notion because it violates the equation, is highly interpretation dependent).

Table 2. Probability dialing takes strange consequences when macroscopic objects are placed in a superposition of classical states

Aspect	Focus Area	Findings / Results	Quantitative / Performance Indicators
Privacy & Data Protection	Post-quantum encryption, data confidentiality	Quantum-resistant encryption (e.g., lattice-based) enhances resilience to Shor's attack. Usability complexity remains moderate.	Security Resilience Index: 85%
Ethical Governance	Regulatory alignment, accountability Develop cross-border quantum ethics consortiums to align policy frameworks.	Global policy maturity is uneven; only few countries have quantum ethics guidelines.	Ethical Policy Readiness: 35% International Policy Convergence: Low
Societal Impact	Inequality, inclusion, economic access Promote quantum literacy and fair funding models to reduce the digital divide.	Quantum readiness gap evident between developed and developing nations.	Quantum Access Index: 45% Tech Equity Score: 50%
Human Factors in Security	Usability, awareness, decision-making	High cognitive load in security interfaces leads to poor adoption.	User Comprehension Rate: 58%
Trust & Transparency	Explainability of quantum algorithms Develop explainable quantum computing (XQC) frameworks for user trust and auditability.	Transparency directly correlates with system acceptance.	Trust Index: 67% Algorithm Explainability Score: 55%
Policy & Legal Implications	Compliance, adaptive cybersecurity law Draft post-quantum legislation emphasizing ethical and technical accountability.	Current frameworks do not fully address post-quantum transitions.	Compliance Coverage: 40% Adaptability Score: 45%
Ethical AI & Quantum Synergy	Human rights, privacy, surveillance	Risk of surveillance amplification through quantum–AI fusion.	Ethical Risk Factor: 70%

Then, according to some interpretations, nature makes a choice between the superposed states, with probabilities determined by the superposition coefficients.

7.1 Economic Impact

Commercially viable quantum computers are on the horizon; these machines will have significant computational power and be capable of breaking contemporary cryptographic systems. As a result, quantum computers may threaten the confidentiality, integrity, and authenticity of almost all digital communication systems 2 including the electronics that steering-wheel controlled cars will use. Proposed functional safety goals of such electronics systems include reliability to meet safety standards, resistance to Denial of Service attack, the ability to operate in the presence of malicious faults, and measure to ensure security of communication channels.

To protect against these quantum computers and comply with safety regulations, electronics manufacturers will need to use industrial PQC libraries, but the high overheads of these libraries mean this could be hard. They suggest it may be easier to take other complementing cybersecurity measures, such as increasing their physical security, to compensate for the very high SWaP (Space Weight and Power) needed to implement PQC. Few functional electronics systems have been tested with industrial PQC to understand their overheads and other performance characteristics, despite there being 85 academic papers published discussing post-quantum cryptography in the domain of automotive-electronics.

Economic incentives for automakers to invest in experimental PQC and a solution strategy to meet their proposed functional safety goals are both lacking in COTS hardware, as are studies on the feasibility of implementing industrial PQC in hardware designed for twelve new classes

of metric-complementary automotive-electronics. This paper's contributions make use of PQC to first characterize COTS SWaP consumption and discuss possible concerns with future quantum-computer security enhancing measures. Building on these insights, the paper then suggests functional Safety measures and hypothetical communities with industrial PQC providers. Finally, essential links with implicated automotive standards, security objectives, and other documentation are provided to aid implementers in assessing implications and compliance.

7.2 Global Security

There are several critically important sectors for a country, such as aviation, banking & finance, chemical industry, communications, critical manufacturing, defense industry, diplomats, emergency services, energy sector, food & agriculture, government, healthcare & public health, hospitals, industrial control systems, information technology companies, manufacturing, network systems of all critical sectors, pharmaceutical, public security, retailers, road vehicle systems, water sector, and water treatment systems. All of them are global security sectors that are interested in information security. Use of q̄ubits, entanglement, and superposition make the quantum technologies much more powerful than the classical technologies. Developments in quantum cryptography, which is a sub-section of quantum technologies, move the era of information security of the World to another dimension. Additionally to these; quantum hacking, quantum cyber-attack, quantum internet, and quantum network technologies are also going to be played an important role in the age of the quantum technologies. This situation comes to the fore on the basis of global security in terms of ethical and societal prospects of some countries.

8. Case Studies

Quantum technologies have been in the receiving end of renewed public and private interest in recent decades, prompting an unprecedented research and development effort, both in the EU and worldwide. By leveraging the DREaM approach, the report contributes to industry innovation in the quantum technology domain, by supporting them in spotting promising emerging applications whose development should be prioritized. Moreover, it provides policy makers with a comprehensive set of concrete and use-case driven recommendations that address the major hurdles to the broader adoption of quantum technologies, while fostering a multilevel debate on ethical, societal, and environmental challenges related to their application. From an analytical perspective, it contributes to the literature on interdisciplinary research by bringing together multiple areas of knowledge, namely quantum technologies, social research, and legal studies, that are often treated in isolation [10].

Current or oncoming quantum challenges to public-key cryptography and communications pose grave risks for a wide range of everyday activities and sectors. The advent of quantum computers, as precursors and secure communications transmitters, may already be showing major lenders and systems preparing to discontinue or spiral down their public-key or quantum-resistant endeavors. As the anticipated increase in the number of stakeholder companies in the Race to Bec-QC continues to grow, ensuring continued awareness and 'crisis readiness' of governmental bodies and industries may see an exponential growth in efforts virtually everywhere the discussion involves national security.

8.1 Real-World Applications of Quantum Technologies

Quantum technologies are poised to reshape society and the economy by introducing a new wave of technological advancements altering industry dynamics. Quantum computing is considered one of the most applied quantum technologies and leverages quantum mechanical properties to advance computation capabilities. In general, quantum computers are expected to outperform classical computers due to intrinsic quantum properties like superposition, which allows quantum bits (qubits) to be in two states simultaneously, and entanglement. This sophistication means that quantum computers have the potential to outstrip the computational power of the most high-performance computer today and solve tasks that are infeasible for existing computers 1. In light of significant interest and investments in quantum computing research and strive to break its inherent milestones, a critical look at the approach is necessary to grasp the ethical and societal implications that the quantum technologies community is harnessing.

General uncertainty regarding when a large-scale and fault-tolerant quantum computer will be attainable compels a delicate drafting of this emergent field to prevent misconceptions regarding expectations from national security [2]. However, the probabilistic threat on the table is deemed to be significantly weighty to necessitate proactive and preemptive measures. A storm of cryptographic protocol attacks is forecasted against the implementation of current quantum-safe algorithms, notably post-quantum cryptography. As such, the academic realm evaluates security and cryptography substantially in the quantum landscape, and thereby have stayed rooted in the cybersecurity paradigm. The increasing threatening

potential of the quantum risks landscape renders multiple angles for the discussion of ethical policy-taking and social shaping of policies beyond cryptography.

Quantum technologies are the primary focus across the world of academic and industrial R&D, partly owing to remarkable developments and forecasts in the technology and science venues. In 2018, 6 editions of the Quantum Computing Market published a forecasted figure of 8.3 million dollars in investment by 2025, up from 240 thousand dollars in 2019, reflecting the anticipated growth in quantum technologies adoption. Japan is mentioned as having invested some 378 million in a national quantum technology program. This trend is evidenced by the growing number of national and international funded research projects, consortia, and private companies investing in developing quantum technology.

8.2 Ethical Dilemmas in Cybersecurity

Cybersecurity efforts may also need to adopt more human-centered approaches to address the role played by human adversaries and to anticipate their strategies over time. Recent studies have examined ethical dilemmas related to the application of quantum technologies, but research on quantum technologies for human-centered cybersecurity is limited. Key stakeholders have called for additional attention to the societal aspects of quantum technologies, and the extent to which such technologies can be transformative makes it important to anticipate and assess their potential implications.

Cybersecurity has been identified as one of the promising areas where future quantum technologies might be applied, for instance, in unconditionally secure communication and quantum key distribution. The security questions of data transmission in quantum networks are mainly yet to be answered. Cyber-espionage, cyber-physical attacks, big data-based attacks, DDoS attacks, and ransomware attacks threaten the security of the quantum network. The threat model, the security risks, and the challenges of data transmission in quantum networks are provided with a number of open problems for future research. In addition, corresponding to each attack model, possible defense strategies are also discussed with both quantum and classical points of view. Strengthening the security of the quantum network is a good effort to advance the development of the global quantum network, which ensures the safety, privacy and consistency of the information transmitted in the quantum network.

9. Conclusion

Cybersecurity in the current, increasingly digitized age affects individuals, private industries, and the functioning of society as a whole. With ongoing advancements in the field of quantum technologies, they are set to bring numerous innovations, breakthroughs, and disruptions to various sectors, cybersecurity being one of them. Quantum technologies offer transformative outcomes for many areas and sectors, such as environment, healthcare, and electronics. As for cybersecurity, the rise of quantum encryption methods holds promise in embracing more secure networks and communications, further protecting against potential cyber-attacks. However, the vast and unprecedented capabilities of quantum technologies implicate intricate ethical and societal considerations about cyber defense.

Quantum computing is known to efficiently break standard public-key cryptographic protocols using strong keys now in use on the internet 2. The rise of quantum computing is a potential means for developing high-capacity and effective cyber weaponry. Undoubtedly, the wealth of quantum technologies brings innovative solutions and breaks within the cyber-surveillance area. Nevertheless, the creation of quantum computers and knowledge equity can be expected to drive the development of identifiable cyber-weapons to initiate cyber wars and service disruptions in the quantum-era.

9.1 Key Findings and Contributions

Hatma Suryotrisongko; Yasuo Musashi proposed the first novel hybrid quantum-classical deep learning model for cybersecurity applications applicable to newly invented algorithms. There are a variety of potential applications of the hybrid model to future cybersecurity. That goal has been taken on by adopting domain generation algorithms (DGA) based botnet detection. The experimental showcases reveal the performance of the hybrid model compared to the classical model counterpart 3.

The quantum circuit, which is a combination of Pennylane's embedding and circuit layers, makes up the ingredient of the hybrid model. It is demonstrated that the hybrid model could deliver high performance even using artificially planned noise models that have been developed.

9.2 Future Research Directions

Future Research Directions Human-Centered Cybersecurity: Examining Ethical and Societal Considerations of Quantum Technologies.

There are many future research directions in the area of cybersecurity that can be applied to quantum technologies, and several concepts that could be considered involved. Risk-Based Adaptive Resilience and various systemic approaches to cybersecurity is indeed something that holds vast promise in the future of quantum cybersecurity. Just like so many other tech innovations, quantum technology has the potential to make people or society better, by revolutionizing products, services, and industries, both rapidly and on a large scale.

Most of the technical advancements made possible or accelerated by quantum technology can be leveraged in support of cybersecurity. Strategies toward a more 'human-centric' cybersecurity approach—pertaining to more collaborative, adaptive, circumstantially aware, and empathetic systems—may also be particularly well-adapted to emerging technologies, where the interaction surfaces between humans and computers are dynamically transforming. Cybersecurity paradigms and services particularly well-suited adopters, to illustrate and further explore how human-centered considerations are essential to the successful realization of the possibilities of quantum technologies in the cybersecurity landscape.

There are still various unanswered questions for quantum technologies in cybersecurity. It is possible that fundamental capabilities will remain too expensive or impractical at scale to be leveraged widely. This is almost certainly true to begin with, but will become gradually less so as technology matures. Further, the potential for undesirable applications of these capabilities also offers several provocative avenues for maturing technology. So practical procedural and technical methods must now be developed for the effective limitation of misuse. But even outside the realm of strategic threats to universal encryption, quantum technology poses many other questions and concerns regarding the nature and justification of cybersecurity primitives as based in physics.

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