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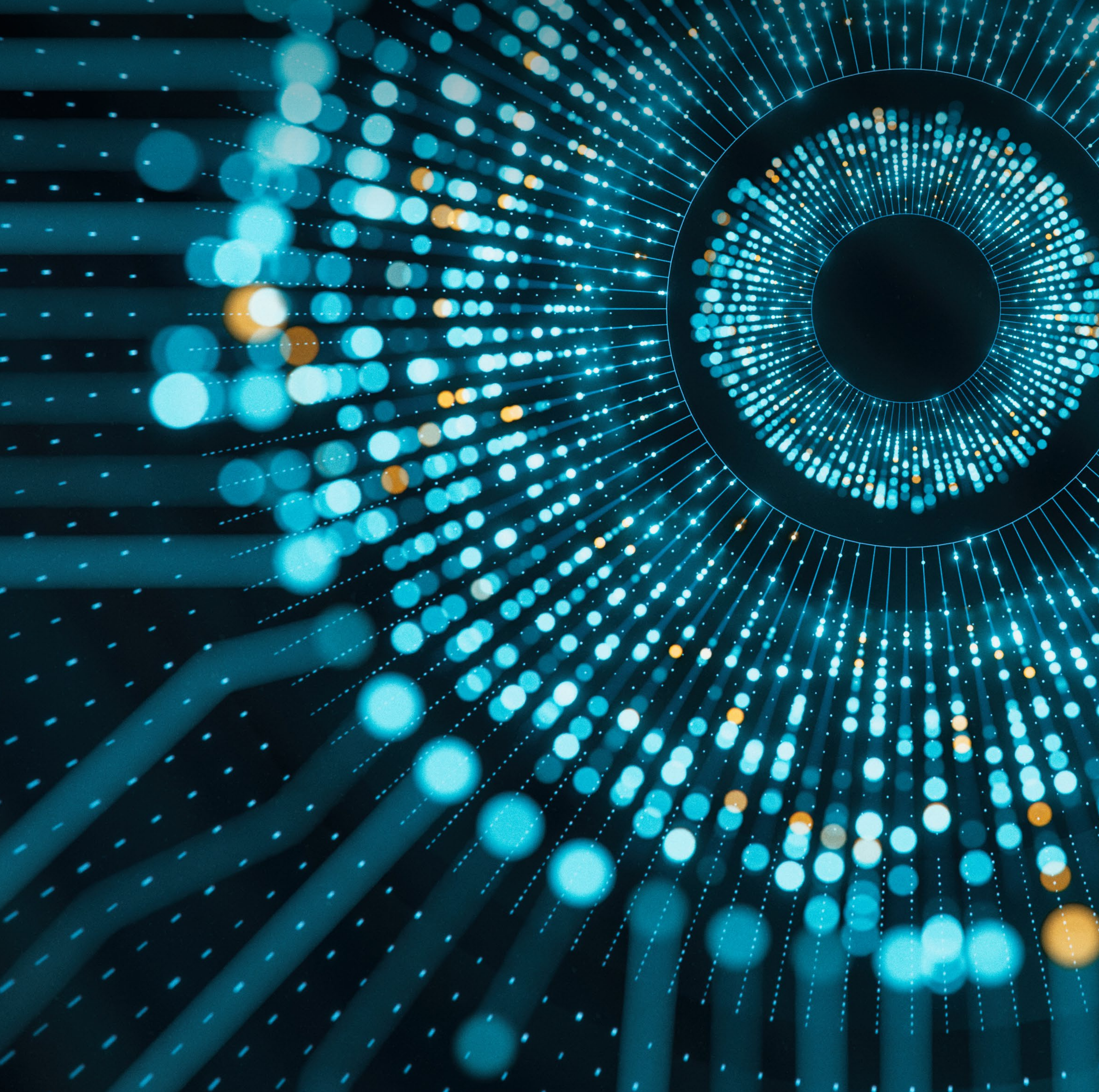
Quantum Technologies:
Key Strategies and Opportunities for ICT Leaders

WHITE PAPER

MARCH 2025



Images: Getty Images

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Foreword

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How can ICT leaders harness the power of quantum and relevant technologies to drive innovations and maintain a competitive edge in the digital age? By strategically adopting quantum innovations, they can revolutionize their industries and secure a sustainable future.

The World Economic Forum and Accenture have been collaborating on the Application Hub initiative to advance the quantum economy for industries and policy-makers. The information and communication technology (ICT) industry, which is the foundation of multiple industries, is poised to gain immense opportunities from quantum technologies. We are committed to enabling the ecosystem and equipping decision-makers to harness quantum technology and drive innovation and growth.

In an era where technological advancements are reshaping industries at an unprecedented pace, integrating quantum and quantum-adjacent technologies into the ICT sector has the potential to drive transformative change, as highlighted in *Embracing the Quantum Economy: A Pathway for Business Leaders*.[1] Furthermore, policy considerations, national initiatives, international guidelines and best practices are key enablers driving adoption of quantum technologies, as noted in *Quantum Economy Blueprint*.[2] This briefing paper aims to provide a comprehensive roadmap for ICT leaders, helping them to strategically harness quantum innovations in computing, sensing, communications and security.

As the world navigates the complexities of the digital and physical landscapes, it is imperative for ICT leaders to deepen their understanding of the risks that quantum technologies introduce and the strategic opportunities they present. They not only promise to revolutionize computational power and data security but also offer unparalleled precision in measurement and detection. By embracing these innovations early, ICT companies and their clients can gain advantages, spearheading future advancements.

This document explores the maturity, learning curve, implementation time and cost, scalability and associated risks of key quantum and relevant technologies. Through use cases, case studies and insights from industry leaders (which are additionally highlighted in the Quantum Application Hub and the Industry Track of the Quantum Economy Network), we highlight the transformative potential of these technologies and provide a clear path for their strategic integration.[3] The frameworks outlined herein will empower the global ICT ecosystem to realize the economic value of quantum and quantum-adjacent technologies, ensuring that companies remain at the forefront of innovation.

We extend our gratitude to the contributors and collaborators who have provided expertise and insights, making this paper a valuable resource for ICT leaders worldwide. Together, we can navigate the challenges and seize the opportunities presented by quantum or quantum-relevant technologies, driving a sustainable and competitive future for the ICT sector.

Executive summary

Quantum technologies are reshaping information and communication technology, demanding strategic preparation for emerging risks and opportunities.

Quantum technologies are poised to transform computing, security and precision measurement, with major implications for the information and communication technology (ICT) sector. This white paper provides a strategic roadmap for ICT leaders to navigate the maturity, implementation timelines and scalability of quantum computing, sensing and communication technologies. It highlights key risks and opportunities, enabling organizations to position themselves for success as quantum capabilities evolve.

Key findings

- **Quantum computing**: Real-world applications are emerging in areas such as 5G network optimization and customer product recommendations. Opportunities explored within key indicators were analysed through use cases that highlight the transformative potential of quantum computing in optimizing legacy telecommunications networks and enhancing customer engagement.

- **Quantum sensing**: This offers exceptional accuracy in measurement and detection, providing significant benefits through efficient 5G and internet of things (IoT) networks. The maturity of quantum sensing technologies is advancing rapidly, however, with many applications transitioning from experimental phases to commercial availability.

- **Quantum communications and security**: These are urgent priorities, as quantum computing threatens traditional cryptographic methods. Early adoption of quantum-safe security measures, such as post-quantum cryptography (PQC), quantum random number generation (QRNG) and quantum key distribution (QKD), is crucial.

- **Government and regulatory frameworks**: These are set up through five strategic initiative pillars for regulators from various countries, emphasizing the importance of regulatory support in cultivating innovation and ensuring the safe deployment of quantum technologies. Nations leading in quantum investment will shape the future digital economy.

To stay ahead, organizations must:

- **Assess quantum readiness**: Evaluate where quantum technologies align with business needs.

- **Develop a strategic roadmap**: Initiate pilot projects within a larger strategic roadmap, harnessing quantum technologies across key areas of the ICT value chain.

- **Invest in quantum-safe security**: Transition to quantum-resilient encryption methods and collaborate with regulators on cybersecurity frameworks.

- **Monitor industry developments**: Stay updated on advancements in quantum hardware, software and global regulations.

As quantum capabilities mature, proactive organizations will lead the next era of digital transformation. By embracing quantum technologies strategically, businesses can mitigate risks, enhance efficiencies and secure long-term competitive advantages. ICT leaders should adopt an iterative test-and-learn approach to integrate quantum technologies, setting strategic objectives and developing a research agenda. Collaboration with industry leaders, academic institutions and regulatory bodies is essential for successful integration. Long-term strategic planning, continuous learning and adaptation to emerging trends will be critical for maintaining competitiveness and driving significant advancements in the ICT sector.

Introduction

How can information and communication technology leaders strategically harness quantum and relevant technologies to drive innovations and maintain a competitive edge in an evolving digital landscape?

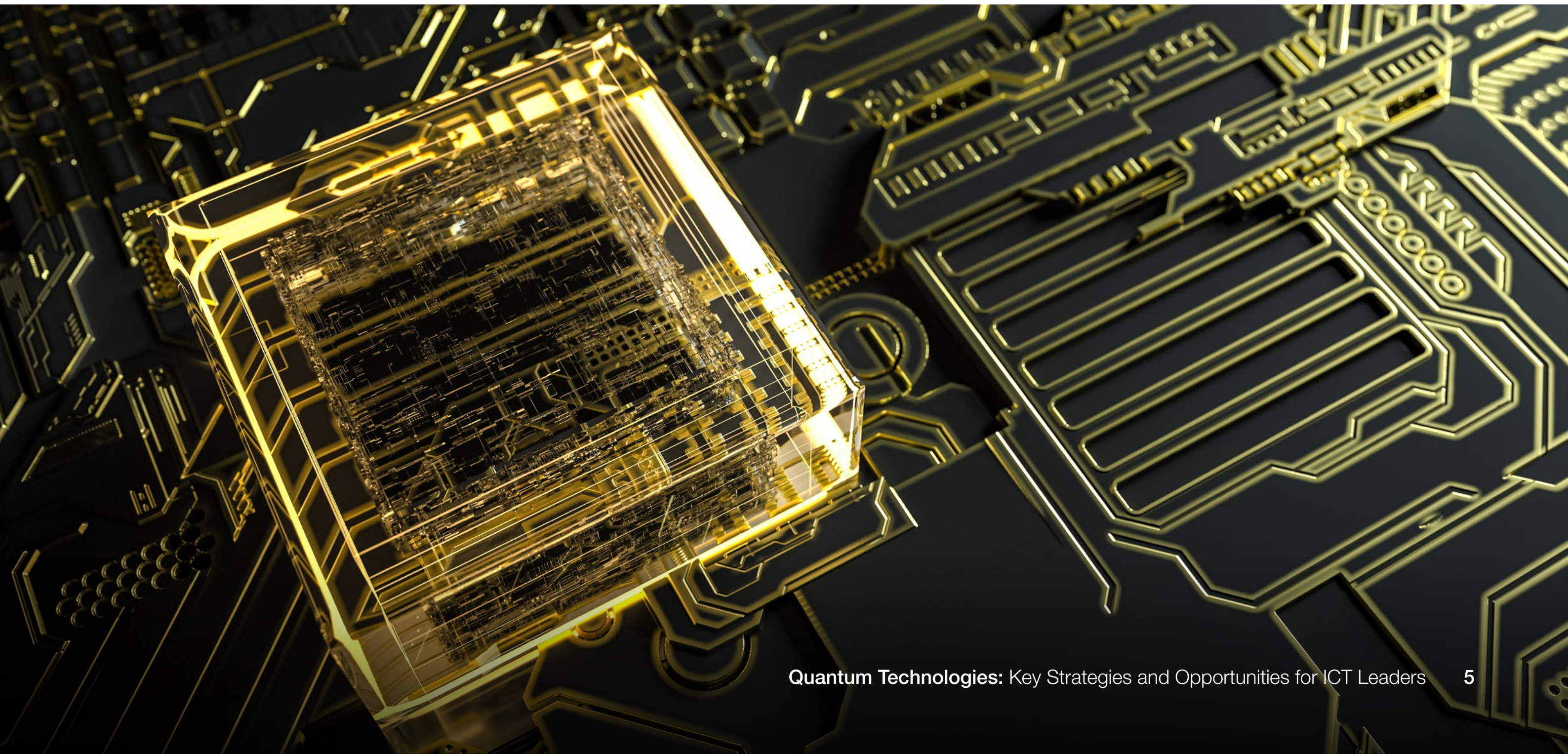
> **By strategically adopting quantum innovations across the ICT value chain, ICT leaders can address both existing challenges and new ones introduced by quantum computers, drive future advancements and maintain a competitive edge.**

This briefing paper delves into the strategic opportunities for information and communication technology (ICT) leaders to harness quantum and quantum-related innovations. For simplicity, “quantum technologies” here refers to both quantum and quantum-adjacent technologies. By examining use cases and case studies addressing challenges and advancements, this document aims to strategically position executives for the future. Understanding the value chain for the ICT community is essential in this context to inform executive readers about potential entry points and the impacts of harnessing quantum technologies. Additionally, a roadmap for each kind of technology – quantum computing, sensing, communications and security – will be laid out, providing a clear path for early adoption and strategic integration. This paper is a resource for ICT companies, helping them to remain at the forefront of innovations and maintain competitiveness in a dynamic landscape.

To effectively adopt these technologies, it is crucial to consider their maturity, learning curve, implementation time and cost, scalability and associated risks. These strategic considerations are supported by insights from the community as well as use cases and case studies from industry and technology providers. The indicators offer guidance for ICT leaders and illustrate the benefits of quantum technologies over time.

Furthermore, the five pillars of the quantum industry outlined in this paper can be applied to help the global ICT ecosystem harness the economic value of quantum technologies. Strategic initiatives for regulators seeking to achieve this goal include research and development (R&D), infrastructure and technology, public-private partnerships, support for start-ups, and education and workforce development. Examples from various countries highlight the importance of regulatory support in cultivating innovations, creating new economic value and ensuring the safe and effective deployment of these technologies.

The integration of quantum technologies into the ICT sector presents significant opportunities for innovation and growth. By strategically adopting quantum innovations across the ICT value chain, ICT leaders can address both existing challenges and new ones introduced by quantum computers, drive future advancements and maintain a competitive edge. This document emphasizes the importance of early adoption, strategic planning and collaboration with industry and regulatory bodies to fully realize this potential.

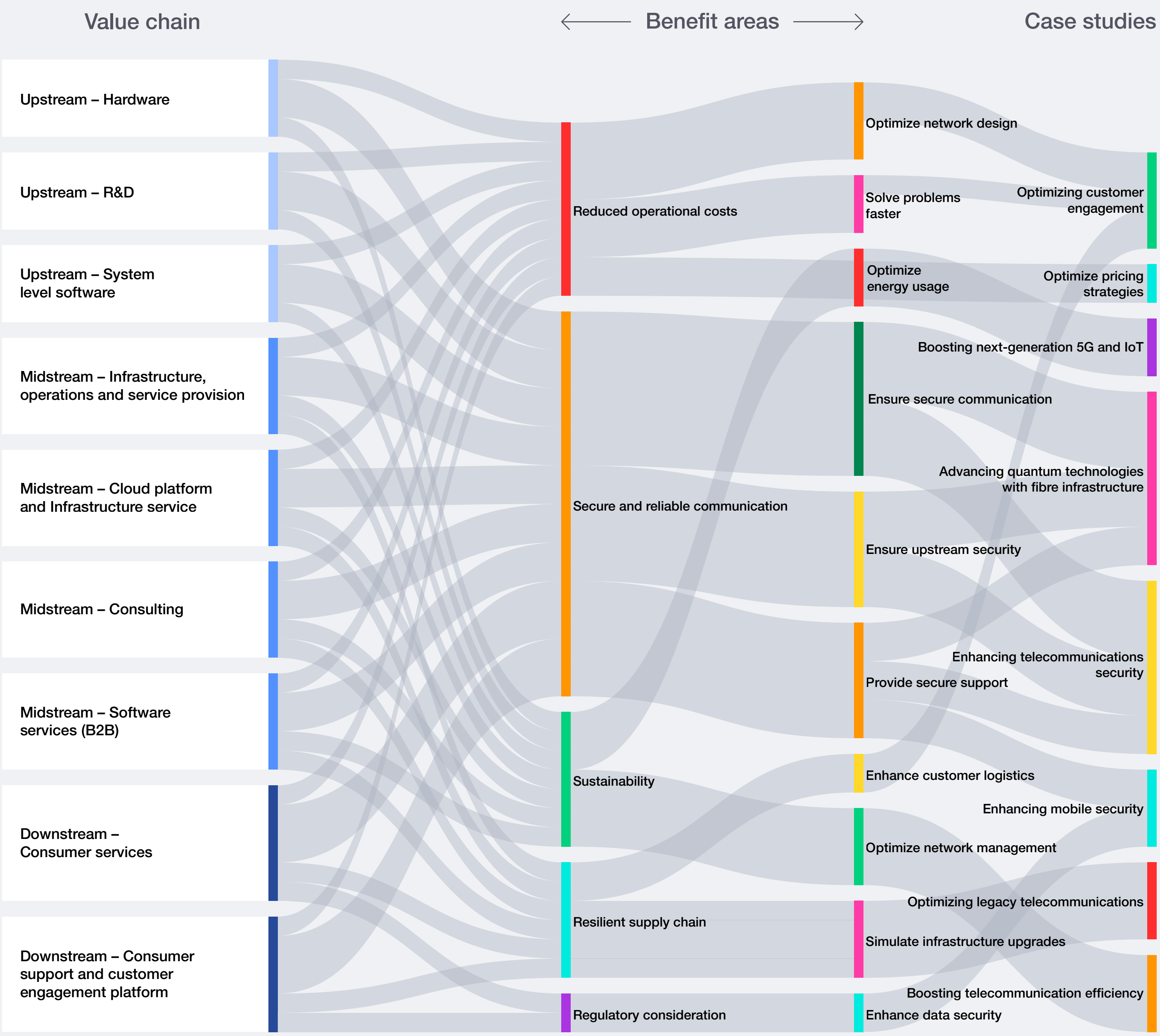


1 ICT and quantum

Quantum technologies have the potential to transform the ICT sector, addressing value chain challenges and yielding benefits for business.

The ICT sector is undergoing swift transformation driven by technological advancements and new integrations accelerated by responses to associated risks. To comprehend the full impact of the changes brought by quantum technologies, it is essential to understand the ICT value chain and its various contributing segments. Figure 1 provides an overview of the ICT value chain, highlighting key segments such as upstream, midstream and downstream, along with their respective sub-streams. It also outlines the challenges posed by emerging trends and current issues within these streams. Furthermore, it illustrates how quantum technologies can benefit each segment of the value chain.

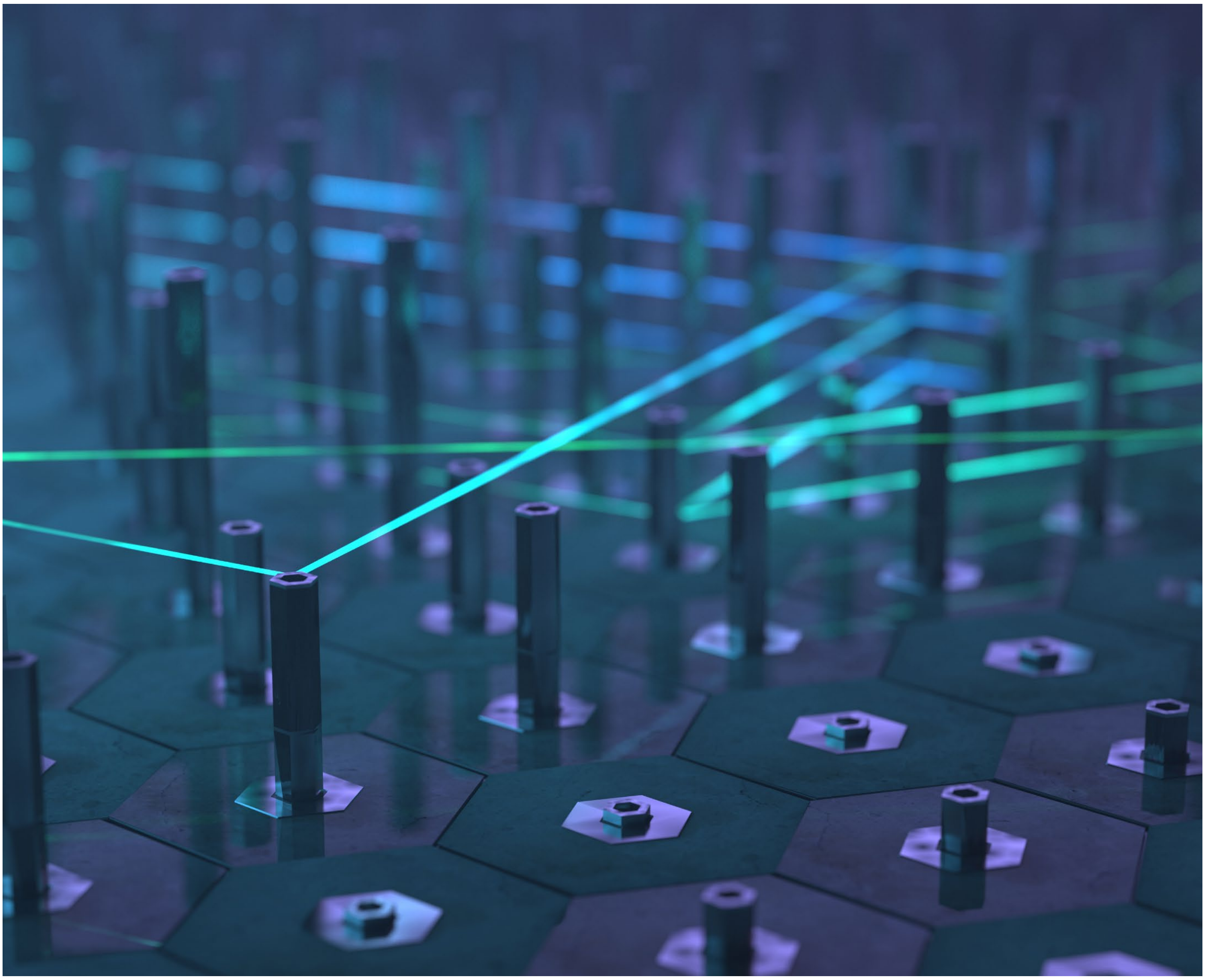
FIGURE 1 **Benefits of quantum technologies for challenges in ICT sectors across the value chain**



Source: Accenture.

The case studies which are explained in detail in the subsequent chapters are mapped to the value chain and benefits (in Figure 1). The maturity of quantum technologies varies, meaning their benefits can be realized at different scales and levels. However, as emerging trends, they offer significant first-mover advantages for ICT companies. Early adopters can gain valuable experience and expertise, positioning themselves ahead of competitors as the technology evolves.

Additionally, the journey to fully harnessing these technologies is a long and complex process. By beginning this journey now, companies can gradually build the necessary infrastructure, skills and partnerships to ensure they are well-prepared to capitalize on the full potential of quantum advancements as they become more practical and widespread. Early initiation mitigates future risks and creates opportunities for innovation and leadership in the evolving ICT landscape.



2

Quantum computing

Quantum computing has the potential to solve complex problems, as highlighted through insights from key indicators.

The maturity of quantum computing technology is still in its early stages, requiring ongoing R&D to achieve practical and scalable solutions.

Quantum computing is uniquely suited to certain types of algorithms and problems, particularly those that increase in complexity as they scale. Quantum computers can solve problems that have numerous possible solutions or involve elements of randomness and uncertainty more efficiently than classical computers.

It is also important to consider some key indicators to understand the status of this technology, including: maturity, learning curve, implementation time and cost, scalability and risks.

The maturity of quantum computing technology is still in its early stages, requiring ongoing R&D to achieve practical and scalable solutions. There are many different technologies being explored, such as gate-based devices, trapped ions, photonic qubits, quantum dots and topological qubits. Each of these technologies has its own unique methods and potential advantages, but they all need further development to reach maturity. However, Fujitsu's quantum-inspired Digital Annealer, developed with the University of Toronto,[4] showcases early application of quantum-inspired solutions to optimize legacy telecommunications networks, reflecting the current maturity level of quantum computing.

The learning curve of quantum computing is substantial, requiring a deep understanding of quantum mechanics, algorithm design and error correction techniques. TIM's use of quantum computing for 5G network planning[5] highlights the practical benefits and manageable learning curve, which can be further reduced through collaboration with providers and experts.

Implementation time and cost are also significant considerations. Deploying quantum computing solutions involves substantial financial and time investments. Ericsson's exploration of using quantum technology to optimize antenna tilting in 5G networks[6] highlights the significant investment in both time and resources required to achieve practical results.

Scalability is another crucial aspect. The Docomo and D-Wave use case demonstrates scalability, illustrating how quantum optimization can address large-scale network challenges. Their pilot project reduced unnecessary signals sent by base stations to mobile devices by 15%,[7] which improved overall network performance and efficiency during busy times.

Finally, while there are risks associated with the complexity of solving real-world problems, quantum computing offers solutions to some of these challenges. The collaboration between Cinfo, QuEra and Kipu Quantum to improve the resilience of MassOrange's telecommunication network in Spain[8] highlights the benefits of using quantum computing and the risks and uncertainties of complex problems, such as optimization in large-scale networks.

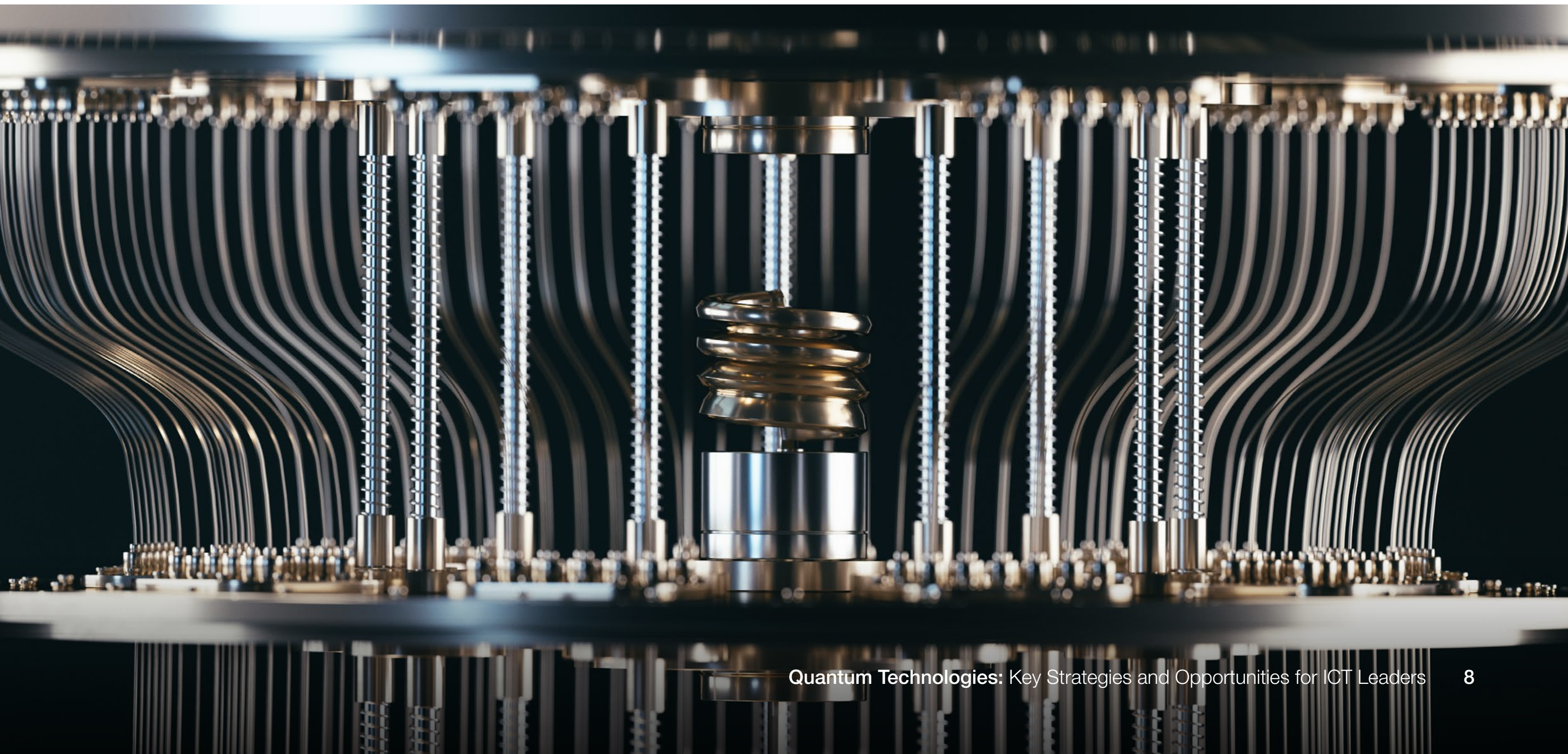


FIGURE 2

Quantum computing

Quantum computing is set to revolutionize industries by delivering unparalleled computational power and enabling breakthrough applications. Strategic adoption of quantum computing technology will provide a competitive edge and drive significant innovations in organizations.

So what?

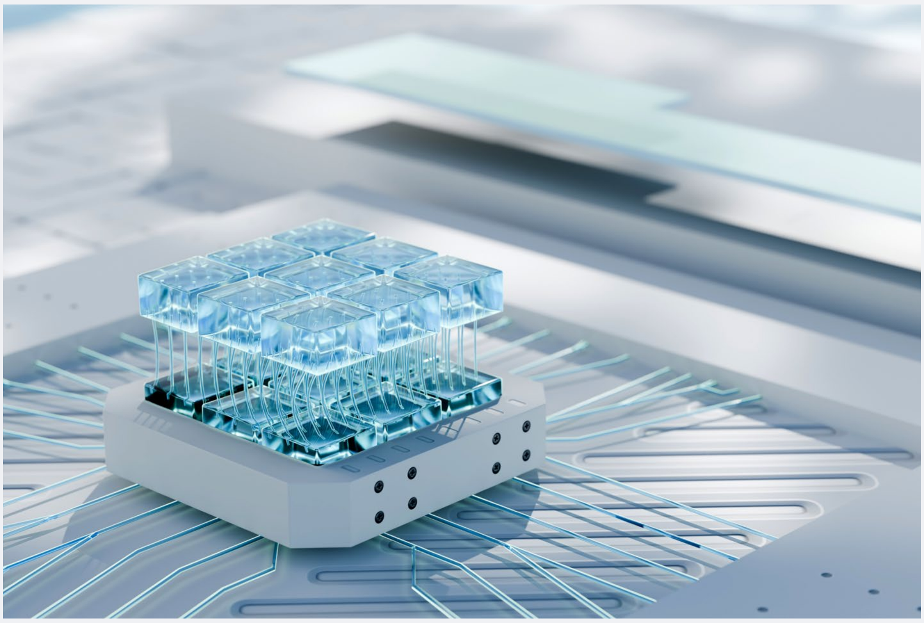
Competitive advantage
Quantum computing will offer superior performance for complex computations, leading to breakthroughs in optimization, cryptography and simulation.

Innovation driver
Quantum computing enhances innovations in ICT by potentially improving data analytics, optimizing network performance and enabling advanced cybersecurity measures.

How?

Strategic exploration of quantum
Identify key areas where quantum computing can add strategic value and develop a detailed plan for its integration into business operations.

Identify use cases
Initiate pilot projects, form partnerships, develop training, prioritize quantum use cases and stay updated on advancements to drive innovations.



Case studies

Optimizing legacy telecommunications with quantum-inspired technology
Value chain segment: midstream – infrastructure, operations and service provision; benefit: reduced operational costs

Legacy systems in industries like telecommunications, logistics and manufacturing have inefficiencies that lead to high costs, resource waste and slow modernization, costing billions of dollars annually. Optimizing and migrating these systems is challenging due to their complexity and traditional methods' limitations. Katsuhiko Arao from Fujitsu stated, "Legacy systems are not just costly to maintain – they also hinder innovations. Our quantum-inspired Digital Annealer technology addresses these barriers, offering rapid, scalable solutions."

Fujitsu, in partnership with the University of Toronto, uses Digital Annealer (i.e. simulates quantum behaviour) to solve large-scale optimization problems. This technology has demonstrated transformative potential, cutting operational costs by up to 30% and transport costs by up to 80% during the network modernization period, typically lasting a few months to a year. The collaboration highlights the importance of academia-industry partnerships in advancing technology. Digital Annealer not only reduces costs but also decreases resource consumption and waste, aligning with global priorities like the Fourth Industrial Revolution and the United Nations (UN) Sustainable Development Goals (SDGs). Fujitsu's work with quantum-inspired computing demonstrates its potential to revolutionize industries, enhance efficiency and support a sustainable, interconnected global economy.

Source: Fujitsu. *(2023). Fujitsu and University of Toronto optimize network transformation with Digital Annealer to help customers significantly cut network operations costs*

Optimizing customer engagement in the telecommunications industry with quantum computing
Value chain segment: downstream – customer support and customer engagement platform; benefit: resilient supply chain

The telecom industry is currently facing significant challenges in engaging customers effectively. With the rapid evolution of services and the increasing complexity of customer interactions, traditional methods are struggling to keep up. AT&T's Next Best eXperience (NBX) proof of concept (PoC) project applied quantum annealing to optimize customer engagement. By analysing customer data, NBX suggests the best sequence of experiences to present during an interaction, balancing customer needs and AT&T's return on investment. This involves using statistical techniques to create propensity scores for each experience, which measure the likelihood of a customer's need and engagement.

With NBX, AT&T aims to determine the optimal sequence of experiences for customers within a specific engagement or timeframe. This PoC project uses innovative methods (such as integer programming and quantum optimizations) to solve this complex problem. The use of quantum computing in NBX not only enhances customer satisfaction and retention but also addresses the growing complexity of the telecommunications ecosystem.

Indicators

1 = Low 5 = High

Maturity	Learning curve	Implementation time and cost	Scalability	Risks
1 — 5	1 — 5	1 — 5	1 — 5	1 — 5

See Appendix A1 for an explanation of indicators.

Action plan

Phase 1
Foundation and exploration

Maturity: Assess available technologies and identify key areas for R&D.

Learning curve: Engage with experts and conduct initial training to build foundational knowledge.

Implementation time and cost: Establish pilot project criteria and evaluate risks and challenges to manage initial investments.

Phase 2
Pilot and scaling

Scalability: Initiate pilot projects and develop integration strategies to test scalability.

Implementation time and cost: Implement training programmes and allocate resources effectively to manage costs.

Risk: Monitor performance metrics and address any technical issues to mitigate risks.

Phase 3
Optimization and leadership

Scalability: Refine solutions and expand quantum computing infrastructure continuously to ensure scalability.

Risk: Cultivate strategic innovations and proactive threat management to handle ongoing risks.

Learning curve: Engage stakeholders regularly to ensure continuous learning and adaptation.

3 Quantum sensing

Quantum sensing is revolutionizing measurement precision, enhancing data accuracy and driving innovations across diverse industries.

The maturity of quantum sensing technologies is advancing rapidly, with many applications transitioning from experimental phases to commercial availability.

The use of cutting-edge quantum sensing provides exceptional accuracy in measurement and detection, offering significant benefits in numerous domains. For example, by harnessing phenomena like superpositions and entanglement, quantum sensors can detect minute changes in physical properties – such as temperature, gravity and magnetic fields – beyond the scope of classical sensors. Adopting state-of-the-art quantum sensors can lead to significant competitive advantages for ICT organizations and improve measurement capabilities.

The maturity of quantum sensing technologies is advancing rapidly, with many applications transitioning from experimental phases to commercial availability. For instance, Qnami's ProteusQ quantum microscope, used to enhance the testing and evaluation of advanced memory devices,[9] illustrates ongoing development and practical use of quantum sensing technologies.

Optimizing implementation time and cost requires substantial investment in research, development and infrastructure. BT's testing of quantum antenna technology for 5G and internet of things (IoT) networks[10] demonstrates the significant amount of funding necessary for the development and adoption of quantum sensing solutions.

Scalability is another crucial aspect of quantum sensing technologies. While these technologies have the potential to be applied across various fields, current limitations in sensor sensitivity and stability need to be addressed. For example, Massachusetts Institute of Technology (MIT) has developed a method that allows quantum sensors to detect electromagnetic signals at any frequency,[11] demonstrating scalability potential. However, these current limitations must still be overcome.

Adopting quantum sensing technologies comes with certain risks, including technological uncertainties, high costs and potential integration challenges. The National Institute of Standards and Technology (NIST) highlights the risks and uncertainties involved in integrating quantum sensing technologies.[12]

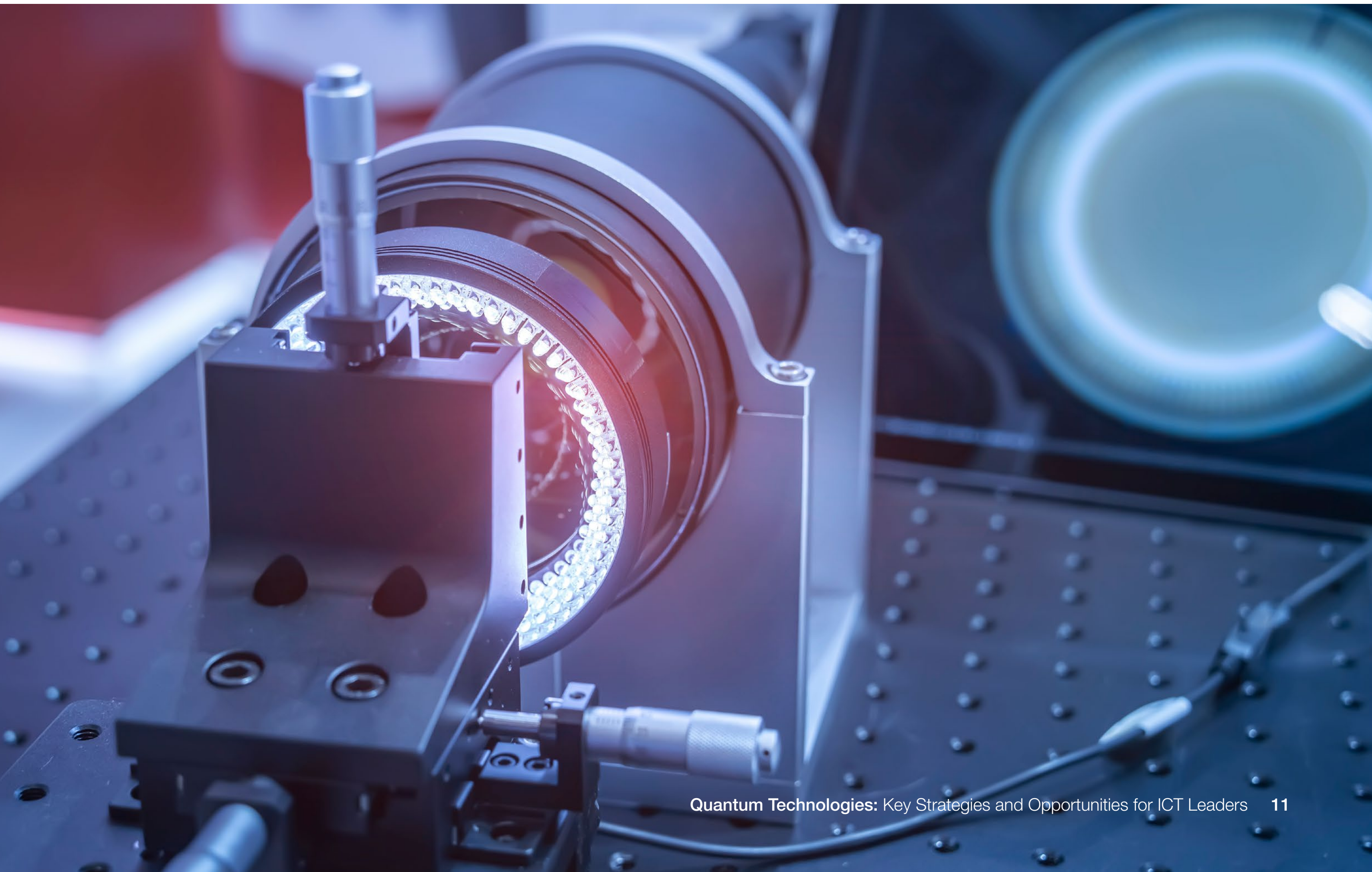


FIGURE 3

Quantum sensing

Quantum sensing harnesses advanced quantum technologies to achieve unparalleled precision in measurement and detection, offering significant advantages in various fields. Adopting quantum sensing technologies will enhance organizations' capabilities in sensing and measurement, driving innovations and competitive advantage.

So what?

Precision and sensitivity
Quantum sensing provides unmatched precision and sensitivity in measurements, critical for advancements in fields like telecommunications and defence.

Strategic advantage
Early adoption of quantum sensing technologies ensures an organization remains at the cutting edge of technological advancements and maintains a competitive edge.

How?

Strategic integration
Identify key areas where quantum sensing can add value and create a strategic plan for its implementation.

Scaling and optimization
Scale successful pilot projects and integrate quantum sensing technologies into core operations for enhanced capabilities.

Case studies

Boosting telecommunication efficiency with Inflegtion's New Quantum Clock
Value chain segment: midstream – infrastructure, operations and service provision; benefit: sustainability

The telecommunications industry is currently grappling with issues such as inefficiencies, high costs and the need for modernization. These challenges are compounded by the complexity of existing systems and the limitations of traditional methods. Timothy Ballance, President at Infleqtion UK, stated, "We are very pleased to be able to deliver our first commercial clock in the UK to Professor Riis and his group at the University of Strathclyde. Tiqker will be rigorously tested by the world-leading experts at the University of Strathclyde, and their feedback will be invaluable as early customer insights."

Infleqtion has achieved a significant milestone with the first UK commercial delivery of its groundbreaking optical atomic clock, Tiqker, to the University of Strathclyde. This collaboration with Professor Erling Riis's research group is set to revolutionize navigation and precision timekeeping. The Tiqker clock offers short-term hydrogen maser-like performance in a compact package, with a Cs-Beam-like holdover of up to seven days (meaning it can still keep accurate time for up to seven days if it loses its primary time source). This innovation is expected to enhance the stability and robustness of positioning, navigation and timing (PNT) technology.

The National Timing Centre (NTC) and National Physical Laboratory (NPL) quantum programmes are developing the UK's first nationally distributed timing infrastructure. These initiatives aim to reduce reliance on global navigation satellite systems (GNSSs) and improve the resilience of critical national infrastructure. The Tiqker clock will play a crucial role in these efforts, supporting the development of next-generation timekeeping technologies. Infleqtion's work with the Tiqker clock demonstrates quantum technology's potential to address current challenges in the telecommunications industry, enhance efficiency and support sustainable, interconnected global infrastructure.

Source: Infleqtion. (2024). *Infleqtion Marks Milestone with First UK Sale of Quantum Clock, Tiqler.*

Boosting next-generation 5G and IoT with quantum radios
Value chain segment: upstream; benefit: sustainability

The telecommunications industry faces significant challenges, including high energy consumption, limited signal sensitivity and the need for cost-efficient solutions to support the growing demand for 5G and IoT networks. These issues hinder the development of more efficient and widespread connectivity solutions. Howard Watson, Chief Technology Officer of BT, stated, "BT's investment in cutting-edge R&D plays a central role in ensuring the UK remains a network technology leader. Our programme has huge potential to boost the performance of our next-generation EE network and deliver an even better service to our customers".

BT is pioneering a trial of potentially hyper-sensitive quantum radio receivers that use excited atomic states to detect much weaker signals than conventional receivers. This technology, based on a quantum effect called "electromagnetically induced transparency", forms a highly sensitive electric field detector. The trial marks the first time a digitally-encoded message has been received on a 3.6 gigahertz (GHz) (5G) carrier frequency, demonstrating potential for significant advancements in network sensitivity and efficiency.

The new quantum radio technology could reduce mobile network energy consumption, enhance the efficiency of IoT devices and support the development of cost-effective smart cities and agriculture. Researchers at BT Labs are working to miniaturize the equipment and optimize radio frequency (RF) – the range of electromagnetic wave frequencies used for wireless communication – modulation and signal processing for future radio networks.

BT's trial of quantum radios highlights the transformative potential of quantum technologies in telecommunications. These innovations stand to enhance network performance, reduce costs and boost progress towards the SDGs.

Source: BT. (2022). *BT trials a new quantum radio to boost next-generation 5G & IoT networks.*

Indicators

1 = Low 5 = High

Maturity	Learning curve	Implementation time and cost	Scalability	Risks
1 — 5	1 — 5	1 — 5	1 — 5	1 — 5

See Appendix A1 for an explanation of indicators.

Action plan

Phase 1
Foundation and exploration

Maturity: Identify and prioritize business areas that could be improved through quantum sensing applications.

Learning curve: Assess available technologies and develop detailed plans for initial pilot projects.

Implementation time and cost: Establish collaborations with vendors and industry to manage initial investments.

Phase 2
Expansion

Scalability: Review and evaluate the outcomes of initial pilots to develop scalable solutions.

Implementation time and cost: Deploy solutions into existing infrastructure and test performance to manage costs.

Risk: Refine and optimize sensing systems to address any technical issues and mitigate risks.

Phase 3
Optimization and leadership

Scalability: Roll out solutions across the organization and explore advanced use cases.

Risk: Engage stakeholders and gather feedback to manage ongoing risks.

Learning curve: Share insights and innovations within the industry to ensure continuous learning and adaptation.

4 Quantum communications and security

Discover the next generation data protection mechanisms using quantum technologies.

> Failure to adopt quantum and relevant technologies for security could lead to serious data breaches and compromise communications.

Future quantum computers could compromise current cryptographic techniques and make them more vulnerable. To ensure business confidence, integrity and availability, companies should adopt quantum-safe security and a defence-in-depth approach. These solutions are explored in detail in Appendix A2.

In terms of the maturity of quantum communications and security technologies, NIST, supported by an international consortium of 25 countries, has standardized the first round of post-quantum cryptography (PQC) algorithms. The US government is leading the charge in regulations, mandating migration to these PQC algorithms, and further work on new NIST candidates is underway.[13] However, QKD may not yet be ready for widespread use in some geolocations (such as the US) due to security concerns.[14] Nevertheless, companies in other regions are proactively testing and implementing QKD and PQC, and China is developing its own PQC algorithms.[15] For instance, TELUS and Photonic's collaboration on a 30 km fibre network[16] demonstrates advancements in quantum communications, computing and networking.

The steep learning curve caused by the complexity and novelty of quantum communication and security is another important factor. Solutions such as QRNG, QKD and PQC require advanced knowledge in quantum mechanics and cryptography. Moreover, they present their own practical implementation challenges. For example, entanglement distribution involves additional complexities related to the fundamental principles of quantum networks and the sharing of qubits, as illustrated by TELUS and Photonic's collaboration.[17]

Implementing quantum-safe technologies is costly and time-consuming, and a smooth transition will require unique infrastructure. Quantum-safe migration should start as early as possible to mitigate the risk of attackers stealing encrypted data in the present with the intention of decrypting it later with future quantum computers (also called "steal now – decrypt later"[18] or "prepare now – relax later"[19]). The Chinese QKD network, spanning 4,600 km,[20] is a successful example of a prepare-and-measure implementation (where the sender prepares quantum states and the receiver measures them). This achievement was made possible through substantial government support, underscoring the essential role of governmental backing.

Scalability must be considered. While QKD offers significant potential, it presents challenges such as high costs and distance limitations. In contrast, PQC does not have the same challenges.[21] Harvard physicists[22] demonstrated this potential by building a metro-area quantum computer network using existing telecommunication fibre. The proposed 800 km QKD network in South Korea, developed by SK Broadband and ID Quantique, protects 48 government agencies.[23] Its modular architecture and interoperability with existing systems make it scalable, allowing for seamless expansion and integration for a QKD network. However, a hybrid approach with PQC is easier to deploy, even in space, with a secure multi-orbit data link featuring crypto-agility.[24]

Failure to adopt quantum and relevant technologies for security could lead to serious data breaches and compromise communications, as sufficiently powerful future quantum computers could break current encryption methods, especially asymmetric encryption (which involves a pair of keys and is currently the foundation for nearly all secure communications). A secure data backup system called H-LINCOS has been developed by the National Institute of Information and Communications Technology (NICT), Japan's primary ICT research institute, and Kochi Health Sciences Center.[25] This innovation highlighted the possibility of addressing these risks by ensuring data integrity and confidentiality even in the face of quantum threats.

FIGURE 4

Quantum communications and security

Quantum communications and security is essential for safeguarding sensitive data in the evolving ICT landscape. Early adoption and strategic implementation can provide a competitive edge and ensure robust protection against future quantum threats.

So what?

Transformative impact
Quantum security technologies and PQC have the potential to revolutionize data protection by addressing vulnerabilities in classical encryption and key exchange methods, especially those compromised by advancements in quantum computing.

Competitive advantage
Early adoption of it can differentiate an organization as a leader in safeguarding data, enhancing trust and compliance.

Compliance with regulation
Help ensure compliance with emerging regulations and standards.

How?

Initial assessment and planning
Assess existing security protocols, cryptographic algorithms, data storage, network infrastructure, authentication, software, industrial control systems, cloud services and communication channels. Identify vulnerabilities that quantum technology could exploit.

Pilot projects
Implement quantum security solutions in a controlled environment to evaluate effectiveness and compatibility. Use pilot results to refine integration strategy and address technical issues.

Case studies

Advancing quantum computing, QKD and networking with fibre infrastructure
Value chain segment: across the entire value chain; benefits: regulatory considerations, secure and reliable communication

Canadian communications technology company TELUS is providing Photonic with access to a 30-km dedicated fibre network in British Columbia, configured to test increasingly complex quantum networking that uses quantum encryption for ultra-secure, tamper-evident transfer of information over long distances. This state-of-the-art infrastructure will enable Photonic to advance capabilities in quantum computing (solving complex problems beyond the reach of today's computers), quantum networking and QKD (using quantum signals to create secure encryption). These technologies are all critical for the future of digital security and innovation.[26]

Stephanie Simmons, Founder and Chief Quantum Officer at Photonic, stated, "This collaboration with TELUS allows us to move from the lab into real-world applications, showcasing the compatibility of our technology with existing infrastructure. It marks a significant step forward in building the foundation for a quantum-ready future that will revolutionize computing and digital communication across Canada and beyond."

The collaboration between TELUS and Photonic aims to address critical challenges in digital security by harnessing QKD, which uses the principles of quantum mechanics to encrypt data with unprecedented security and makes interception attempts immediately detectable. Additionally, quantum computing's ability to solve complex problems at a scale unattainable by today's computers has transformative potential across industries like finance, healthcare and logistics.

This initiative not only enhances data security but also supports economic growth by positioning Canada as a leader in quantum technology. The advancements made through this collaboration are expected to attract investment and facilitate innovation, contributing to the country's technological and economic development.

The collaboration between TELUS and Photonic underscores the importance of industry partnerships in advancing quantum technology. By introducing innovative quantum solutions, the organizations are paving the way for a more secure and efficient future. This case study highlights the transformative potential of quantum communication and its critical role in supporting a sustainable, interconnected global economy.

Source: TELUS. (2024). *TELUS and Photonic join forces to build Canada's quantum future.*

Enhancing mobile security with QRNG
Value chain segment: downstream – consumer services; benefits: regulatory considerations, secure and reliable communication

The telecommunications industry faces significant challenges in ensuring the security of sensitive data on mobile devices. With the increasing reliance on mobile phones for activities such as banking, health data management and online shopping, the risk of cyberattacks and data breaches has escalated. Traditional security measures are often insufficient to protect against sophisticated threats, necessitating advanced solutions.

Yoo Chul-joon, Head of SK Telecom's Smart Device CT department, stated, "The Galaxy Quantum 5 is the latest in the Quantum series, now with premium performance and artificial intelligence (AI) features, further enhancing its completeness. We aim to offer security and AI capabilities at a reasonable price through the Galaxy Quantum 5 and will continue our efforts to ensure our customers enjoy a convenient telecommunications experience."

The Galaxy Quantum 5, developed by ID Quantique and SK Telecom, integrates quantum technology with Samsung Knox to enhance mobile security. It features the world's smallest QRNG chip, measuring just 2.5 by 2.5 mm, which generates truly random numbers to strengthen authentication and data encryption. This ensures that sensitive information (such as fingerprints and payment details) is safeguarded against potential breaches. The device also offers improved AI capabilities for photography as well as a refined design. A quantum indicator notification lets users know when quantum security services are active, while the QRNG operates continuously in the background to maintain security integrity. ▸

Case study (continued)

The partnership between ID Quantique and SK Telecom underscores the importance of integrating advanced quantum technology into mobile devices to address current security challenges. By harnessing the world's smallest QRNG chip and Samsung Knox, the Galaxy Quantum 5 offers a robust solution for protecting sensitive data. This case study highlights the transformative potential of quantum technology in enhancing mobile security and supporting a sustainable, interconnected global economy.

Source: ID Quantique. (2024). *SK Telecom unveils the Samsung Galaxy Quantum 5.*

Enhancing telecommunications security with PQC
Value chain segment: across the entire value chain; benefits: regulatory considerations, secure and reliable communication

The telecommunications industry is currently grappling with the impending threats posed by quantum computing. As quantum technology advances, the risk of quantum-empowered attackers decrypting sensitive data becomes a significant concern.

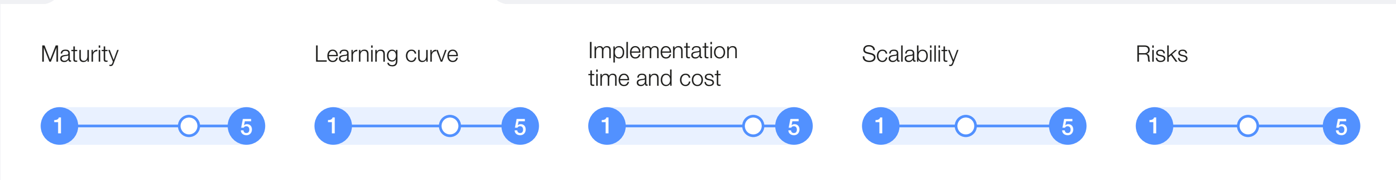
Emma Smith, Vodafone's Cyber Security Director, explained, "On one hand, quantum computing has the potential to rapidly solve ultra-complex problems in key areas such as healthcare, but on the other it could undermine today's cryptography. This is why we are playing an active role in the transition to a quantum-safe world."

SandboxAQ worked with telecommunications organizations, such as Vodafone and Softbank,[27] to trial and evaluate PQC-ready secure networking using PQC algorithms based on NIST standards in real-life scenarios. Today, SandboxAQ collaborates with multiple telecommunication organizations on cryptography inventory and assessment projects to enhance cryptographic management, improve security and ensure compliance with key standards. Such initiatives are part of a broader effort to protect customers, governments and society from future quantum threats through a phased and planned migration to PQC.

Similarly, the PQC Coalition, including members like SandboxAQ and Microsoft, aims to accelerate the adoption of PQC to safeguard sensitive data. By harnessing advanced cryptography and cultivating industry collaboration, the sector can better prepare for a quantum-safe future for itself and customers.

Source: Vodafone. (2023). *Vodafone tests Quantum-safe business network with upgraded smartphones.*

Indicators 1 = Low 5 = High



See Appendix A1 for an explanation of indicators.

Action plan

Phase 1
Awareness and assessment

Maturity: Formulate a quantum and PQC strategy and assess the current security and cryptographic landscape.

Learning curve: Engage with experts and develop a risk management framework.

Implementation time and cost: Benchmark industry standards and draft a strategic roadmap.

Phase 2
Implementation and integration

Scalability: Pilot quantum and PQC solutions and evaluate their effectiveness.

Implementation time and cost: Integrate and transition legacy systems, conduct comprehensive security testing and roll out training programmes.

Risk: Forge strategic partnerships for continuous management and address any technical issues.

Phase 3
Optimization and leadership

Scalability: Optimize security solutions and expand quantum security infrastructure.

Risk: Monitor emerging threats, revise security strategies and engage in industry innovations.

Learning curve: Plan for the integration of next-generation quantum technologies and advancements.

5 Strategic pillars for policy makers and ICT innovators

Empowering the global ICT ecosystem requires strategic vision, initiatives and investments to propel the quantum economy.

To cultivate a sustainable innovations pipeline and harness significant economic value, regulators should engage the quantum industry through five pillars – **R&D, infrastructure and technology, public-private partnerships, start-ups and private ventures, and education and workforce** – using targeted incentives to drive growth and ecosystem engagement. The following sections present a detailed overview of these insights, supported by successful initiatives from across the globe.

5.1 R&D

A strong foundation of R&D is vital for advancing the quantum economy. Regulators should prioritize funding for fundamental and applied research, and cultivate multidisciplinary initiatives that combine quantum physics, computer science and engineering to address complex challenges. Mechanisms such as government grants, tax incentives and academic collaborations can drive innovations while ensuring transparency and inclusivity. For example, the World Economic Forum's *Technology Policy: Responsible Design for a Flourishing World* white paper underscores the necessity of regulation in the ICT industry to stimulate innovation and seed critical quantum technologies for economic growth.[28]

5.2 Infrastructure and technology

Developing a robust infrastructure is critical for the growth of the quantum ecosystem. Governments should create favourable environments that promote investment in quantum data centres, secure communication networks and specialized hardware labs, and support scalable infrastructure like quantum internet testbeds and regional hubs. Long-term planning should ensure integration with existing ICT systems and lay the foundations for global quantum networks. *Regulating quantum technology applications: government response to the RHC*[29] highlights the establishment of quantum hubs and the National Quantum Computing Centre (NQCC) by the Digital Regulation Cooperation Forum (DRCF), offering actionable guidance for transitioning to quantum-secure systems and aligning technologies with public interest protections. The International Telecommunication Union's (ITU's) Database of Standards[30] includes global quantum standards, covering network and security aspects like QKD and PQC. It also supports international collaboration and helps ensure the smooth deployment of interoperable quantum technologies.

5.3 Public-private partnerships

Public-private partnerships are essential for accelerating quantum innovations, bringing together government, academia and industry stakeholders to effectively commercialize technologies. These collaborations enable sharing of resources, expertise and risk, expediting the transition from research to real-world applications. For instance, the National Quantum Initiative Reauthorization Act[31] in the US highlights the value of such partnerships, authorizing prize challenges and supporting efforts to strengthen the resilience of the quantum supply chain. Regulators play a key role in facilitating these collaborations to ensure equitable access and maximize benefits.

5.4 Start-ups and private venture

Encouraging start-up companies and attracting private investment is vital for the growth of the quantum economy. Regulators can cultivate entrepreneurship through incentives, incubators and streamlined processes, while derisking early-stage ventures with grants or government-backed investments. Initiatives like India's National Quantum Mission (NQM),[32] which supports start-ups such as QNu Labs and QpiAI, demonstrate how targeted support can help build a robust ecosystem. Similarly, Australia's $940 million investment in PsiQuantum drives targeted acceleration towards the establishment of a commercially viable quantum computer in Brisbane.[33]

5.5 Education and workforce

A skilled workforce is essential for the development of quantum technologies. Regulators should support educational initiatives that provide professionals with expertise in quantum mechanics, programming and engineering. The National Quantum Initiative Reauthorization Act[34] by the US Association for International Migration (USAIM) has facilitated the establishment of a quantum education and workforce hub, which addresses barriers impeding the commercialization of innovations (also called the "valley of death"). Similarly, NQM's Jai Anushandhan vision emphasizes collaboration between academia and industry, guiding institutions on how to align with national goals and cultivating a talent pipeline to support the quantum sector's growth.

By aligning policies with these five pillars, regulators can lay a strong foundation for the quantum economy, drive progress and address critical challenges in the quantum technology landscape.

Conclusion

How can ICT leaders shape the future using quantum technologies? Integrating quantum technologies into ICT promises a new era of innovations and growth. ICT leaders should align actions with plans to capture these opportunities. This paper recommends an iterative test-and-learn approach, allowing decision-makers to take "no regret" initial steps, learn and use the results to inform the overall roadmap. It is essential to set strategic objectives and develop a research agenda to achieve them.

FIGURE 5 **Strategic initiatives and benefits of quantum technologies**

	Strategic initiatives	Benefits
Quantum computing	Develop comprehensive strategies, which may also align with regional and national objectives. Invest in infrastructure necessary to secure access to quantum compute resources. Launch pilot projects to explore boundaries of technology.	Reduce barriers of entry to using quantum and learn the limits of technology to solve complex problems. Focus on strategic business challenges whose solutions contribute to competitive advantages. Accelerate identification of real-world challenges to develop more efficient solutions.
Quantum sensing	Understand the impact of quantum sensing on strategic objectives. Conduct research that tests quantifiable hypotheses with current quantum sensing technologies. Prioritize projects using the most mature technologies.	Quantum sensing improves high-impact areas by providing more accurate and reliable data. Investing in proven technologies ensures faster adoption and scalable solutions, leading to quicker returns and lower risk. A data-driven approach reduces uncertainty, helping organizations make smarter decisions with clear goals, testing and expert insights.
Quantum communications and security	Catalogue current cryptography assets. Develop a defence-in-depth strategy. Develop PoCs for PQC and QKD solutions to implement and integrate them.	Prevent the potential threat of a quantum computer-based attack Use enhanced cryptographic techniques as a competitive edge to businesses offering more secure solutions. Remain compliant with emerging regulatory environments.

ICT company positions itself at the forefront of technological innovation, driving business value and maintaining leadership in the industry.

Source: Accenture.

Collaboration with industry leaders, academic institutions and regulatory bodies is essential for the successful integration of quantum technologies. Public-private partnerships, R&D initiatives and supportive regulatory frameworks will play a pivotal role in driving the quantum economy. The regulatory landscape for quantum technologies emphasizes the need for global alignment on standards to ensure stable deployment. Collaboration with regulators is crucial to address cybersecurity, data privacy and ethical concerns. Adaptable regulations will allow organizations to keep pace with quantum advancements, ensuring the secure, ethical deployment of these technologies. Examples across countries underscore the importance of regulatory support in cultivating innovation and ensuring the safe and effective deployment of quantum technologies.

Integration of quantum technologies is going beyond mere exploration, with researchers combining quantum computing, quantum sensing and quantum communication and security to create more powerful and versatile systems. For example, fusing trapped atom arrays with photonic devices enhances scalability and computational speed in quantum computing.[35] Additionally, the convergence of quantum computing and AI, known as quantum AI, is opening new possibilities in fields like sensing and machine learning.[36] The integration of various quantum technologies is paving the way for a comprehensive and powerful quantum ecosystem.

Long-term strategic visions in sectors like ICT offer substantial benefits by facilitating innovation and stability, propelling strong partnerships and collaborations. These extended horizons encourage investment in transformative technologies, with ICT serving as a critical enabler across industries. Quantum technologies can introduce further cost savings and efficiencies, amplifying potential financial and operational improvements across sectors.

As quantum technologies continue to evolve, ICT leaders must remain agile and forward-thinking. Long-term strategic planning, continuous learning and adaptation to emerging trends will be critical for maintaining competitiveness. By embracing the transformative potential of quantum technologies, ICT leaders can drive significant advancements, ensuring a sustainable and innovative future for the sector.

Appendices

A1 Explanation of indicators

These indicators also influence one another, with risk being particularly affected by the combined impact of all other factors.

TABLE 1 **Indicator explanations**

Indicator	Explanation of indicator levels	Quantum computing	Quantum sensing	Quantum communications and security
Maturity How developed and ready the technology is for practical use	**1 (very low)** – Experimental stage, mainly theoretical, no real-world use cases **3 (moderate)** – Some proven applications, but large-scale deployment is limited **5 (high)** – Well-developed, widely adopted and integrated into various industries	Between **very low** and **moderate** Early-stage technology with promising but limited practical applications	**Moderate** Some technologies (atomic clocks, magnetometers) are mature, but scalability is an issue	**Moderate** Technologies like quantum key distribution (QKD) and post-quantum cryptography (PQC) are mostly in use, but widespread adoption is still evolving
Learning curve The effort and expertise required to adopt and use the technology	**1 (very low)** – Very complex, requiring deep expertise in quantum physics and engineering **3 (moderate)** – Specialized knowledge required, but practical applications are more intuitive **5 (high)** – Easy to learn and integrate, with user-friendly tools and widespread training available	Between **moderate** and **high** Requires deep quantum mechanics knowledge, but programming tools like Qiskit are emerging	**Moderate** Moderate complexity; applied fields like medical imaging and navigation are easier to understand	Between **moderate** and **high** Complex field requiring knowledge of quantum cryptography, entanglement and network security
Implementation time and cost The resources required to deploy the technology	**1 (very low)** – Expensive, ong-term investment with slow deployment **3 (moderate)** – Moderate cost and time commitment, with potential long-term return on investment (ROI) **5 (high)** – Cost-effective and quick to implement at scale	Between **very low** and **moderate** Expensive and long-term investment required, with gradual improvements	**Moderate** Some sensors are deployable now, but widespread use is costly	**Moderate** High initial costs for infrastructure but improving with industry investments
Scalability The ability of the technology to expand and handle increasing workloads	**1 (very low)** – Limited scalability due to hardware, cost or environmental requirements **3 (moderate)** – Some expansion possible, but significant improvements are needed **5 (high)** – Easily scalable, deployable across industries with minimal barriers	Between **very low** and **moderate** Requires massive infrastructure (cryogenics, vacuum systems), making scaling difficult	Between **very low** and **moderate** Some sensors can be miniaturized, but others need complex environments	Between **very low** and **moderate** Infrastructure-heavy (fibre optics, satellites) and has distance limitations
Risks Potential challenges or negative outcomes from adoption or non-adoption	**1 (very low)** – Minimal risk, well-established technology with clear benefits **3 (moderate)** – Some uncertainties, but risks can be managed with strategic planning **5 (high)** – Significant risks, including high costs, security vulnerabilities or potential disruptions	Between **moderate** and **high** High costs, uncertain timelines and future risk to encryption	**Moderate** Integration challenges and high initial costs but moderate long-term risk	Between **moderate** and **high** Risk of delayed adoption leading to cybersecurity vulnerabilities

A2 Solutions to counter quantum threat

There are two very different classes of solutions, which should be combined to counter the quantum threats of the future.

The first class of solutions, which relies on computation, aims to replace existing algorithms that are vulnerable to quantum computers with new ones, known as quantum-resistant algorithms (QRA). These approaches are often referred to as post-quantum cryptography (PQC). These are entirely based on mathematics implemented on classical computers and do not involve quantum technologies. PQC will undoubtedly form the first line of defence and will be exploited in all general-use applications. Several PQC algorithms have now been standardized by the National Institute of Science and Technology (NIST) to replace the quantum-vulnerable ones currently in use.[37] Organizations are steadily working out implementation. There must be a period where both current and PQC algorithms work concurrently, making the transition more complex than simply replacing a few algorithms. Telecommunication companies are harnessing cryptographic inventory, analytics and PQC to enhance security for government, customers and society.

The second class of solutions is based on quantum technologies. It includes both quantum random number generation (QRNG) for key generation and other cryptographic purposes, and quantum key distribution (QKD) for sharing keys across networks in a secure manner. When implementing QKD, there's a vital choice between using the earlier and more widely used prepare-measure approach or a newer, more-advanced quantum-entanglement approach.

QRNG can be used to generate randomness for most applications. It is the most mature application of the quantum technologies. QRNGs are available in different formats and form factors, for applications ranging from small IoT devices, smart phones, computers and data centres. Some are even space-qualified for use in satellites and some harness 5G smartphone equipped with a QRNG chipset.[38]

QKD has a more targeted application and is used to enhance security in specific applications. It requires physical infrastructure and hardware components, which must be added to existing network infrastructure. Its initial application was direct data centre to data centre connection, with a limited maximum distance of the order of 100 km. Today, this has expanded to encompass terrestrial fibre networks with longer distances and complex connectivity. Several large networks are now operating or in various stages of completion worldwide, including the QKD networks in China, the Euro-QCI in EU, the Nation-wide Quantum Safe Key Distribution Network in South Korea and the Nation Quantum-Safe Network Plus (NQSN+) in Singapore.[39] Since QKD networks require physical infrastructure, they are best designed and operated by telecommunication organizations. The NQSN+ is a good example of a QKD and PQC network operated by a telecommunication organization for various types of customers.

These two classes of solutions have very different pros and cons and should therefore be combined if possible to offer the best defence-in-depth security.

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Acknowledgements

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Endnotes

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