International Journal of Engineering Research and Advanced Technology (IJERAT)

DOI: 10.31695/IJERAT.2025.9.1

E-ISSN : 2454-6135

Volume. 11, No.9
December – 2025

QUANTUM INTERNET

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ABSTRACT

Today's Internet is a global communications network used to transfer, process, and store classical information. The quantum Internet is a hypothetical high-speed Internet that provides ultra-secure connectivity to quantum devices across the globe. It is a network of quantum computers that will someday send, compute, and receive information encoded in quantum states. It is a communications network that will transform industries, increase security, and alter the way we transmit information. While quantum computers exist in the physical world, the concept of quantum Internet is currently theoretical. In its infant form, the quantum Internet promises to make the digital domain safer, more productive, and more powerful than ever before. In this study, we provide a primer on quantum Internet, which provides a large-scale application of advanced quantum communication technologies and protocols.

Key Words: Internet of Things (IoT), Quantum Computing (QC), Quantum Internet, Technology.

1. INTRODUCTION

The quantum Internet is a theorized network of interconnected quantum computers that will one day allow people to send, compute, and receive information using quantum technology. It will not replace the modern or "classical" Internet; instead, it will provide new functionalities such as quantum cryptography and quantum cloud computing.

Its purpose is to serve as a coexistent network that can be used to solve specific types of problems. The classical Internet transmits data using bits that exist as 0s or 1s, relying on electrical or optical signals. On the other hand, the quantum Internet uses qubits, which can exist in superpositions of both 0 and 1. The quantum Internet represents a paradigm shift in how we think about secure global communication [1]. This advanced form of networking allows for the secure transmission of quantum states between distant nodes.

2. QUANTUM COMPUTERS

A quantum computer (QC) behaves according to the laws of quantum mechanics. Thus, quantum computers are different from binary digital electronic computers based on transistors. A major difference between classical and quantum computing lies in the way they encode data. While a digital computer requires that the data be encoded into binary digits (0 or 1), quantum computers use quantum bits, which can be in superpositions of states [2]. In other words, instead of storing information in bits as conventional digital computers do, quantum computers use quantum bits, or qubits, to encode information. (Qubits are the basic units of quantum information.) In addition to ones and zeros, qubits have a third state called "superposition" that allows them to represent a one or a zero at the same time. Figure 1 shows the comparison between the bit and qubit [3]. The computing power of a QC grows exponentially with the number of qubits it uses.

Quantum computers have the potential to perform certain calculations significantly faster than any digital computers. QC consists of a quantum processor which operates at a very low temperature (a few tens of mK) and an electronic controller which reads out and controls the quantum processors, as shown in Figure 2 [4]. Several forms of physical media (optical fibers and free space) can be used to deliver quantum information. Figure 3 shows a representation of quantum computing [5].

In quantum system, the computational space increases with the size of the system. This enables exponential parallelism which leads to faster quantum algorithms. Unlike classical computers, QC offers massive parallelism within a single piece of hardware. A typical quantum computer is shown in Figure 4 [6].

The basic building blocks of quantum computers include quantum gates, quantum memories, quantum CPUs, quantum languages, and Quantum Algorithms [7,8]:

First, quantum computers require Q*uantum Gates*, which are not in the same category as the classical Boolean gates in ordinary computers (e.g., AND or XOR).

A *Quantum Gate* operates on the superpositions of various basis states of qubits and does unitary actions on quantum states, which result in quantum circuits. They have applications in quantum error correction and experimental quantum information processing, as well as solutions in superconductors, linear-optical tools, and quantum dots. Specifically used quantum gates are CNOT and SWAP.

Second, *Quantum Memories* hold quantum systems in a quantum register to process information, and they are implemented using non-moving quantum states. Quantum computers will likely have limited memory.

Third, quantum computers require *Quantum CPUs*. These use a quantum bus for communication between the functional elements of a quantum computer. From a computing perspective, quantum CPUs can be approached through quantum adders.

Furthermore, *Quantum Languages* enables the creation of an artificial quantum computer to simulate a quantum computing environment. The programming language should follow a functional programming structure, which can compute the process as a whole entity with a proper bounded structure.

Finally, *Quantum Algorithms are* significantly faster than any classical algorithm in solving some problems. Most successful quantum algorithms use quantum Fourier transforms because they require less hardware. Popular quantum algorithms include Shor's algorithm (since integer factorization is faster) and Grover's search algorithm.

In ambitious attempts to realize practical quantum computers, enormous effort is still being devoted to designing software (quantum algorithms) and developing hardware (physical implementation).

3. QUANTUM INTERNET

Over the last 50 years, networks have changed every aspect of our lives. Today's Internet connects us globally and plays a vital role in everyday life. It sends packets of information that carry our communications through optical fibers, copper wires, or by microwaves to make wireless connections. The classical Internet sends data from the source to destinations at high speeds. Each source and destination has a unique IP address. The next phase of the Internet will be quantum. The quantum Internet will arrive incrementally.

The quantum Internet represents a significant advancement in secure, high-integrity communication. The need for a quantum Internet comes from the growing vulnerabilities of our current communication systems. The quantum Internet promises a future where secure, instantaneous, and global quantum communication is a reality [9]. The quantum Internet is shown schematically in Figure 5 [10]. The schematic depiction includes a quantum switch, quantum repeaters, quantum computers, quantum channels, and users.

4. APPLICATIONS OF QUANTUM INTERNET

The quantum Internet is a cutting-edge paradigm that uses the unique characteristics of quantum technology to radically alter communication networks. It will be particularly useful for problems that involve many variables, such as analyzing financial risk, encrypting data, and studying the properties of materials. We will not understand everything the quantum Internet can do until it has been fully developed. Common areas of application include the following [11-13].

DOI : 10.31695/IJERAT.2025.9.1

a) Quantum Teleportation

Scientists around the world are working on a quantum Internet to communicate by teleportation. Quantum teleportation is a way to transfer an unknown quantum state from one particle to another at a distant location, without sending the original particle itself. In quantum teleportation, the properties of quantum entanglement are used to send a spin state (qubit) between observers without physically moving the involved particle. Quantum teleportation has the ability to provide quantum connectivity securely between geographically distant nodes. The ability to teleport quantum states through existing infrastructure represents a monumental step towards achieving a quantum-connected computing network. In 2024, a quantum state of light was successfully teleported through more than 30 kilometers of fiber optic cable amid a torrent of Internet traffic, a feat of engineering once considered impossible. Figure 6 shows some fiber optic cables [14].

b) Quantum Networks

Quantum networks use the quantum properties of photons to encode information. Existing quantum networks currently do not expand beyond research rooms, but they relate to quantum computing. The quantum Internet will rely on the laws of quantum mechanics to control and transmit information. The strengths of quantum networks are complementary to those of classical networks.

c) Quantum Internet of Things

Internet of things (IoT) is a worldwide network that connects devices to the Internet and to each other using wireless technology. The quantum Internet of things (QIoT) is an emerging concept that combines quantum computing and quantum communication with IoT to create a highly secure and efficient network of interconnected devices. This can enhance the Internet of things (IoT) through faster data processing, improved security, and complex problem-solving. Quantum IoT has the potential to significantly influence how we live our lives, whether via improvements to machine learning, logistic optimization or financial risk analysis.

d) Quantum Satellite Network

Governments and private companies worldwide, including the US, EU, and China, are already funding multi-billion-dollar quantum initiatives to speed up the development of this technology. China is currently leading in both quantum computing and quantum Internet infrastructure. It has made major progress in quantum communication, notably through its Micius satellite, which was launched in 2016 as part of the Quantum Experiments at Space Scale (QUESS) project. A satellite is shown in Figure 7 [12]. China plans to launch additional satellites into low and medium Earth orbits by 2027.

e) Quantum Initiatives

Several governments and companies are interested in the development of quantum Internet because of the high level of security and communication benefits it would bring. Realizing the extreme potential that quantum Internet offers, government bodies have already launched their initiatives to support the development of this emerging technology. As mentioned earlier, China has been a leader in this area. The European Union is developing its quantum communication systems through the European Quantum Communication Infrastructure (EuroQCI) initiative. Quantum Internet Alliance in Europe is building the world's first full-stack quantum Internet prototype network, and steering the European quantum Internet ecosystem to new heights. US efforts have been given a boost by the US Department of Energy's announcement that it would spend as much as $625 million to fund two to five quantum research centers. The move is part of the US National Quantum Initiative signed into law by President Donald Trump in December 2018. This brings the United States to the forefront of the global quantum race, ushering in a new era of communications.

5. BENEFITS

The structure of the quantum Internet allows for the parties to realize distributed computations with advanced security and extended possibilities compared with traditional networking. A quantum Internet holds promise for accomplishing quantum metrology and quantum computer networks as well as quantum communication among arbitrary clients all

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over the globe. One of the hallmarks of quantum transmissions is that they are exceedingly difficult to eavesdrop on as information passes between locations. Other benefits include [10,15,16]:

The primary advantage of quantum Internet is U*nshakable Security*. Security is the first practical concern. It is the main benefit of a quantum Internet. In other words, one of the key features of quantum communication is its security. The quantum Internet enhances security through quantum key distribution (QKD). Unlike traditional encryption that can be compromised, powerful quantum computers, QKD leverages quantum mechanics to generate and distribute encryption keys. If a hacker intercepted a qubit in transit, the qubit's state would change, rendering the gathered information useless, while the individual sending and receiving the communication would be immediately aware of the attack.

The second benefit includes *Quantum Cryptography*: Quantum cryptography is based on the ideas of quantum mechanics and information theory. New potential in cryptography emerges with advances in quantum cryptography that exploit the quantum-mechanical principle of no-cloning. The regular Internet encodes data encryption using bits (0s and 1s) and relies on encryption methods vulnerable to hacking. On the other hand, the quantum Internet uses qubits, which can potentially exist at the same time due to superposition. This new technology is poised to offer ultra-secure communication through quantum cryptography, making it hacker-proof. Figure 8 shows quantum cryptography [17].

The third benefit is *Synchronization.* Timing and phase synchronization among different nodes is essential for the secure and reliable operation of the different protocols in a communication network. Timing synchronization is also necessary for network traffic engineering and assessing the network performance metrics. Current communication networks use an atomic master clock for synchronizing. The slave clocks in the network use a global navigation satellite system. Next-generation quantum clocks can improve timing synchronization by leveraging quantum entanglement and quantum squeezing.

6. CHALLENGES

One of the main challenges of building a functional quantum Internet is the loss of quantum signals over long distances. The quantum information gets lost once you try to copy or "amplify" it. A major challenge is to provide an optimal solution for transmitting entangled systems, optimizing the network architecture, and developing networking services connected to the entanglement distribution. Other challenges include the following [11,18]:

One of the challenges is the High *Cost.* The cost of building the quantum Internet is still hard to estimate accurately. The cost of building and maintaining quantum networks is currently very high because of the specialized hardware and extreme operating conditions required. It is expected to require billions of dollars in investment over the next decades. On top of that, most of the technology is still in its early stages, so economies of scale have not fully kicked in yet.

Second, there are H*ardware Limitations.* Quantum hardware is still in the development phase, with many devices being unstable, slow, or limited in capacity. Current quantum repeaters and processors can only operate over short distances and timescales. Once hardware performance and durability improve, quantum networks can become practical for real-world applications.

The third is *Scalability.* The current quantum networking systems are complex to expand beyond small-scale experiments. Building a global quantum Internet will require reliable repeaters, more robust qubit systems, and scalable error-correction protocols. Until those technologies mature, connecting multiple nodes over long distances will pose significant technical and engineering challenges.

Fourth, the *Lack of Standardization:* The lack of standardization across quantum networking protocols, interfaces, and hardware is slowing progress. As the field advances, establishing shared standards will enable compatibility and accelerate development. Without them, fragmented systems could emerge.

Interoperability is another challenge. Interoperability between the classical and quantum Internet will be a consideration as the two run in parallel. The two Internets will run in parallel for a long time. The quantum Internet will not immediately displace the classical Internet but complement it.

DOI : 10.31695/IJERAT.2025.9.1

There is also an issue of *Collaboration:* As we venture into this uncharted territory, the collaboration, creativity, and commitment of the global community will be our most valuable assets. Like any advance in technology, progress will ultimately unfold through collaboration. This collaboration will need to cover a wide range of organizations, including research institutions, technology companies, government bodies, regulatory agencies, and international organizations.

Furthermore, *Reliability* is another challenge. The classical Internet generally operates reliably, but the reliability rate of data packet transfer is not always guaranteed. The quantum Internet might experience qubit loss, a problem similar to packet loss. Qubit loss, also known as quantum decoherence, is a phenomenon that frequently occurs when components in a quantum environment interact with a system, leading to photon loss.

Finally, *Decoherence* is seen as another challenge. Imperfections are present in all communication modes, and quantum communication is not an exception. These imperfections result from decoherence. Quantum communication occurs when wave functions of quantum states travel from Alice to Bob through free space or fiber-optic channels. In physics, two waves are said to be coherent if they maintain a fixed phase relationship with each other or change phase over time. The phenomenon of loss of quantum information in the environment with time is known as decoherence. Due to decoherence, quantum states lose their properties and enter the world of classical physics. Decoherence is irreversible and affects the entire communication process, including quantum teleportation and entanglement generation.

7. CONCLUSION

Although it is not clear when a full-scale global quantum Internet will be deployed, researchers estimate that interstate quantum networks will be established within the United States in the next 10 to 15 years. While the quantum Internet has moved beyond the theoretical, scientists are still perfecting much of its essential hardware, including the components responsible for generating, transmitting, and synchronizing qubits. While technical and engineering challenges remain, ongoing progress in quantum hardware, networking protocols, and simulation tools is accelerating development. This includes the development of quantum routers, repeaters, switches, and other networking devices capable of handling quantum information.

The Internet could one day become a global, quantum-secured information super-highway through which anyone can share sensitive data without it being hacked. Computer networks will become so robust that we will always have a fast, reliable connection to the Internet. You could communicate with anyone you choose no matter where you are with no worries about interruption in service. Quantum computers already exist, marking the reality of the quantum Internet in a not-so-distant future. It is only a matter of time before the world sees the quantum Internet. More information about the quantum Internet can be obtained from the books in [19-24].

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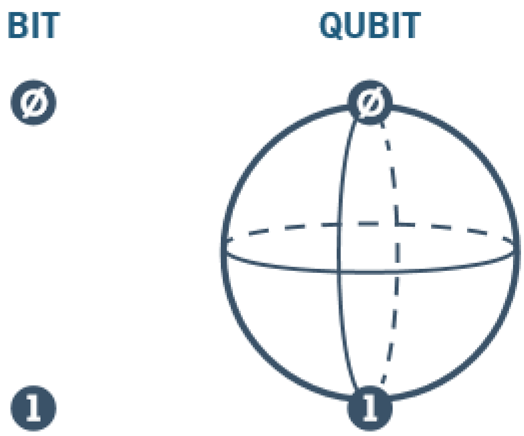

Figure 1 The bit and the qubit [3].

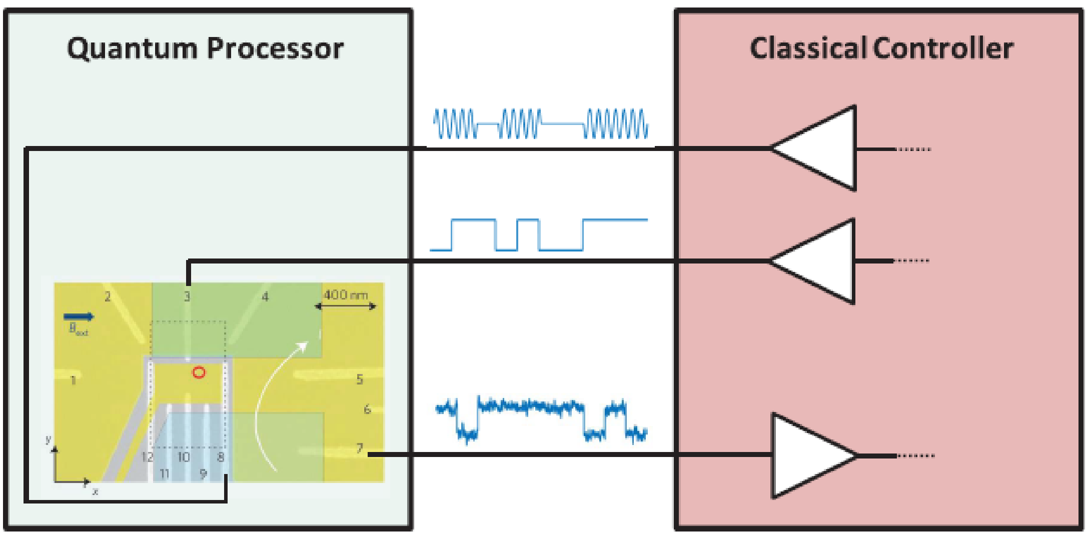

Figure 2 Quantum processor and classical electronic controller [4].

DOI : 10.31695/IJERAT.2025.9.1

Figure 3 A representation of quantum computing [5].

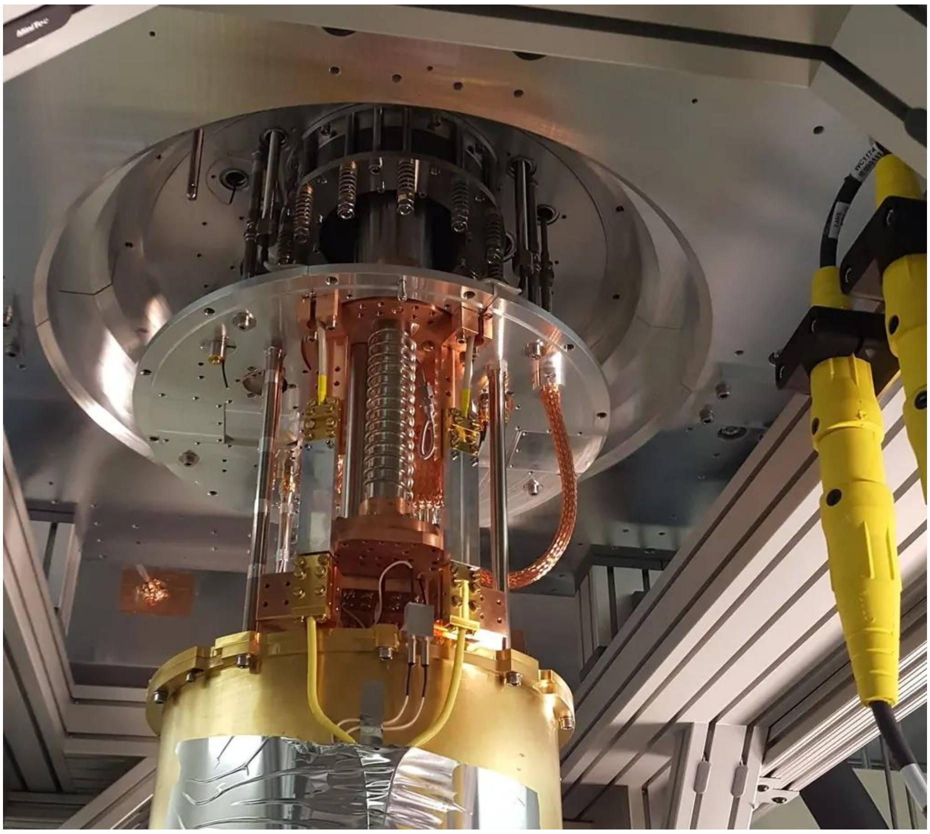

Figure 4 A typical quantum computer [6].

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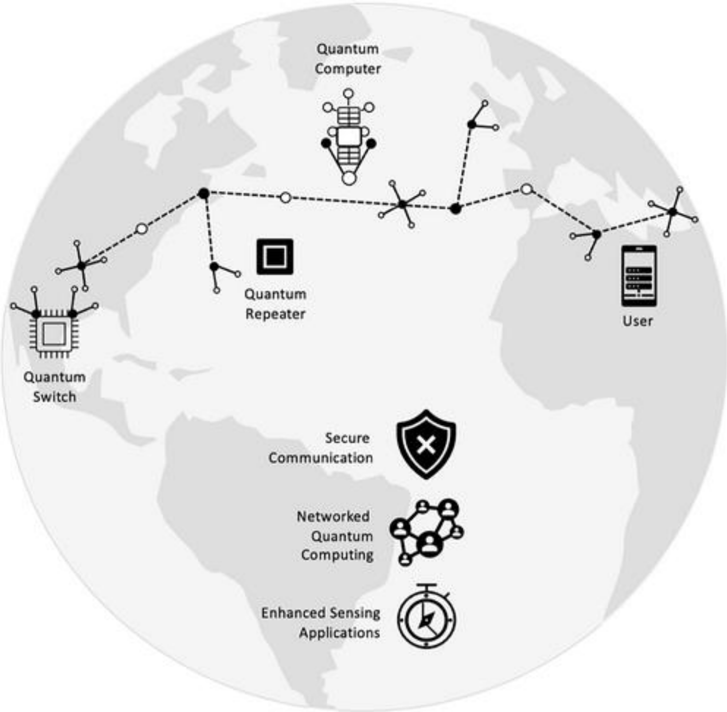

Figure 5 Schematic depiction of quantum Internet [10].

Figure 6 Fiber optic cables [14].

DOI : 10.31695/IJERAT.2025.9.1

Figure 7 A satellite [12].

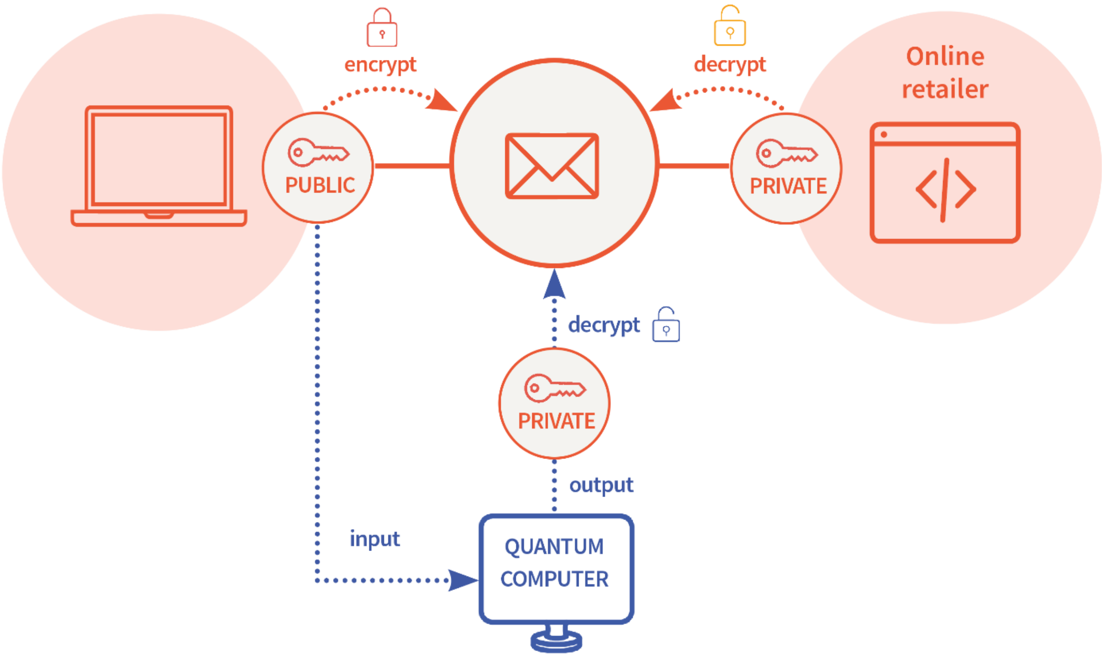

Figure 8. Quantum cryptography [18].

DOI : 10.31695/IJERAT.2025.9.1