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Quantum Technologies: Quantum Communication

Quantum Communication: Global Landscape and Potential Applications for the Brazilian Air Force

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Abstract

Quantum communication exploits the principles of quantum superposition and entanglement to provide advantages over classical communication. It has emerged as one of the key branches of quantum technologies, offering significant disruptive potential compared with its classical counterparts. Among quantum technologies, quantum communication is one of the most mature, having already been successfully demonstrated through both optical fiber and free-space links, including satellite-based communication. This paper discusses the fundamental concepts of quantum communication, reviews the current global landscape with emphasis on European, American, and Chinese initiatives, and examines its potential applications in the context of air power.

1. Introduction

Quantum communication is a research area that has attracted great interest from both a theoretical and practical standpoint. Based on the principles of Quantum Mechanics, quantum communication makes it possible to transmit information securely, as it is impossible to intercept without being detected [1]. This characteristic makes quantum communication a promising option for various applications, including military applications [2].

Within the scope of the Brazilian Air Force, the implementation of quantum technologies aligns with the concept of versatility set out in the National Defense Strategy. Versatility allows for changes in military posture while maintaining the ability to carry out a wide range of tasks. This includes offensive or defensive capabilities against targets in air, submarine, surface, land, cyber, and electromagnetic environments, as well as the ability to participate in single-service, joint, or multinational operations. This is essential for addressing the different levels of readiness required by various scenarios [3].

Regarding quantum sensors, quantum computing, and quantum communication, it can be observed that they are the result of an advance in the field of quantum information technologies, which aims to process, communicate, and store quantum information [4], and therefore share a common foundation. In this scenario, the need for information security during communication in a military setting stands out, making it essential to have reliable, robust, and secure communications to ensure the protection of information. In this sense, advances in the research and development of quantum communication in the military sphere will also be useful for the development of related fields.

1.1. Methodology

This article adopted a methodology involving detailed research and literature review. To obtain relevant information on the subject, documents from academic databases were analyzed, as well as journals specialized in quantum communication and related technologies. In addition, reports, official publications, and documents from government agencies and research institutions were analyzed, aiming to gather data on the global landscape of quantum communication and its applications for the Air Force.

A qualitative analysis of the information collected was car-

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ried out through the review of the selected studies, identifying trends, technological developments, advances in the field, and practical application cases of quantum communication in aerospace environments. This made it possible to offer a broad and concise overview of the global quantum communication landscape, addressing recent advances, promising trends, and possible specific applications for the Air Force.

In summary, this article provides a comprehensive overview of quantum communication and its potential impact on the Air Force and military contexts. Section (2) covers the fundamental principles, basic components, and applications of quantum communication; Section (3) presents advances in Europe, the United States, and China, highlighting China's leadership and the European and American interest in remaining competitive in the field. Finally, Section (4) analyzes the possibilities of using quantum communication in military contexts, including ground communication, air-to-ground and air-to-air communication, and space communication.

2. Quantum Communication

Quantum communication can be defined as a form of transmitting information based on the principles of Quantum Mechanics [5]. Although it is still a relatively incipient field, considerable investment [6] is being made to advance quantum communication both from a theoretical standpoint – through the proposal of new methods and algorithms [7] – and a practical one – through the improvement of the *hardware* involved [8].

Although there are different proposed *hardware* architectures for quantum communication, its foundation consists of a quantum emitter and receiver connected via a quantum channel through which information transmission occurs [5]. In this context, emitters are devices that emit photons or other quantum states of light, which are used to store information that will reach the quantum receivers. Among the possible emitter architectures, semiconductors [9], diamond centers [10], and structures based on isolated molecules and atoms [11] stand out.

In addition to emitters, quantum communication also relies on quantum receivers that receive and decode the information contained in the photons flowing through the quantum channel, which can be optical fiber, vacuum, or even air [12]. Quantum receivers, in turn, can be precise single-photon detectors [13], interferometers [14], or "quantum memory" devices [15] – capable of storing information for a long time.

The combination of such components (emitter, receiver, and channel) makes quantum communication an area with uses in various contexts. The quantum protocol, *i.e.*, the set of rules governing how quantum information will be transmitted and decoded, will determine how that particular application works. In this regard, achieving more secure communication stands out [16], since it is impossible to intercept a quantum channel without being detected. This principle can be extended to virtually any situation involving confidential communication, such as the transmission of military codes and banking data.

In this context, quantum key distribution (QKD) stands out, in which two parties use quantum emitters and receivers to generate and decode a secret key used to encrypt sensitive messages [17]. In addition to the aforementioned high level of security, QKD also has the advantage of theoretically being able to exchange keys over greater distances than current classical protocols without loss of information fidelity [18].

Quantum communication can also be used in the construction of quantum networks, which can be used to connect different quantum devices, with applications in quantum computing [19]. Other important applications of quantum communication include building more accurate sensors, which can have repercussions in various industry sectors [20].

Despite many recent advances in quantum communication, there are still points for improvement that need to be addressed. The main current challenges lie in mitigating the effect of noise and external interference on quantum emitters and receivers, which are still highly sensitive to such effects [21]. Furthermore, extensive research is also being conducted to practically increase the range of current quantum communication [22], while maintaining information fidelity at a level compatible with existing classical protocols.

3. Global Landscape

This section discusses the main advances in quantum communication in Europe, the United States, and China.

3.1. European Landscape

European policy regarding research and development in technologies related to quantum communication stems from the *Framework Program Horizon*, which is currently in its ninth version [23]. Broadly speaking, this program defines a Strategic Research Agenda [24], outlining goals and expected achievements in various areas, including quantum communication. This agenda includes the development of devices and systems for quantum networks, as well as the exploration of protocols that leverage the unique properties of quantum communication.

Europe has a strong commitment to the research and development of quantum communication. Through the launch of the Quantum Manifesto [25], Europe demonstrated its interest in leading the second quantum revolution, seeking to strengthen its capabilities in quantum technologies and create a profitable knowledge-based industry. In addition, Europe is strongly committed to driving research and innovation in quantum communication, seeking to become a global leader in this field.

Currently, the United Kingdom, Germany, and especially Denmark stand out as strong players in this landscape. In 2022, Denmark was selected as the host country for the new NATO Quantum Technologies Centre, and the Novo Nordisk Foundation announced an investment of 1.5 billion Danish kroner in the development of a fully functional quantum computer, which led the Danish government to launch a new strategy for quantum research and innovation in 2023. The strategy aims to maintain a long-term focus on quantum research and innovation, ensuring that Denmark remains at the forefront and plays a key role in the future of quantum technology. Denmark's strong quantum ecosystem, combined with the new strategy, makes it an ideal destination for foreign companies interested in investing and establishing research and development partnerships in quantum technologies [26].

In July 2023, the European Commission launched a call for tenders to develop a testing and evaluation infrastructure for QKD technologies as part of the European Quantum Communication Infrastructure Initiative (EuroQCI), funded with EUR 16 million from the Digital Europe Programme [27]. This infrastructure plans to evaluate and certify QKD technologies developed in the European Union with respect to compliance with security standards and specifications, contributing to European autonomy in quantum communication. The service contract will run until the end of 2027. The infrastructure will be composed of ground and space components, with European Union technologies being used for its development. It will also be interoperable with the secure space connectivity initiative. The actions supported by the Digital Europe Programme will be complemented by other programs and funding sources, including the aforementioned *Framework Program Horizon* [23] and the *Connecting Europe Facility*, as well as funding from the Recovery and Resilience Facility [27].

3.2. American Landscape

The American landscape in terms of the development of technologies related to quantum communication remains within the scope of Research and Development. The United States has treated the subject as strategic since the inception of its science and technology policy. United States science and technology policy was established by the National Science and Technology Policy, Organization, and Priorities Act of 1976 to provide advice to the President. Under this policy is the Subcommittee on Quantum Information Science (SCQIS) of the National Science and Technology Council, which aims to maintain and expand U.S. leadership in quantum information science and its applications over the next decade [28].

In terms of recent advances, in 2022 the SCQIS launched strategic plans for workforce development for the implementation of quantum sensors, seeking to promote economic opportunities, security applications, and scientific advances through the development of quantum technologies [29]. At the same time, the Biden administration launched policies and initiatives related to quantum communication and computing, identifying key steps to maintain the U.S. competitive advantage [30]. Recently, reports from the U.S. Government Accountability Office (GAO) indicate that the Department of Defense (DOD), the Department of State, the Department of Homeland Security (DHS), and the Office of the Director of National Intelligence (ODNI) assessed that "quantum communications could enable adversaries to develop secure communications that U.S. personnel would be unable to intercept or decipher" [31].

In 2023, the National Quantum Initiative Advisory Committee (NQIAC), an advisory body to the President and to the SCQIS, released a report with recommendations to maintain American leadership in quantum technologies. In order to foster the development of revolutionary technologies in quantum computing and simulation, quantum networks and communication, and sensing and metrology, the report concludes that the development of these technologies is a critical factor for the U.S. economy and national security [32].

3.3. Chinese Landscape

China is undoubtedly the country at the forefront of the global landscape in terms of quantum communication research and development. China stands out as a pioneer in building large-scale quantum communication infrastructure, overcoming previous limitations and expanding the potential applications of this technology [33].

In a brief timeline, in 2008 Chinese physicist Pan Jianwei decided to return to China and make the University of Science and Technology of China (USTC) his primary research institution. He moved his laboratory and projects from Heidelberg, Germany, to the Chinese city of Hefei, also bringing some of his Chinese students with him. Even after receiving an additional €1.4 million (US$1.5 million) in funding from the European Union that year, he went ahead with the move. Since his return, China has regularly announced advances in the field of quantum communication. In 2016, Pan and his team launched the world's first quantum satellite into space [34]. In the fall of 2017, they used the Micius satellite to conduct the first interception-proof video conference between Beijing and Vienna [35].

In 2021, Chinese scientists managed to establish the world's first integrated quantum communication network, combining more than 700 optical fibers on the ground with two ground-to-satellite links, enabling QKD-based communication over a distance of 4,600 km [36]. This achievement represents an important milestone, indicating that quantum communication technology can be used in large-scale practical applications. It also suggests the possibility of establishing a global quantum communication network by combining the national quantum networks of different countries.

In March 2023, Chinese researchers announced that they are developing a quantum communication network using satellites in low, medium, and high Earth orbits. The network will enable large-scale QKD-based communication. The Chinese initiative was included in a list of strategic technological megaprojects for advances through 2030. The construction of a global quantum communication network is underway, demonstrating China's commitment to research and development in this field [37].

4. Potential Applications in the Employment of Air Power

The use of technologies within the scope of quantum communication has important implications for military applications, providing secure communication, precise navigation, and precise detection, making it a promising area for improving military capabilities. In general, these characteristics enable the detection of possible espionage and ensure greater resistance against cyberattacks [38].

That said, with regard to the implementation of a quantum communication network based on QKD, in order to analyze the potential military applications in a quantum warfare domain, Fig. 1 illustrates the various forms of connection in a military scenario:

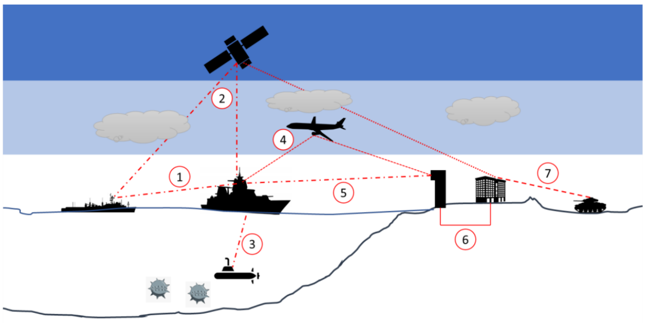

Fig. 1. Examples of military uses of QKD connections [2]

Each number in the figure represents a communication *link*. Most use free-space QKD communication, including (laser) communication between ships (1), satellites (2), submarines (3), aircraft and/or remotely piloted aircraft (4), ground stations (5), and vehicles (7). In addition, an optical fiber communication channel between two ground stations is shown (6). Fiber optic communication also enables QKD between strategic ground-based assets, such as headquarters, command posts, naval stations, and air bases, which generally have a fixed or semi-static location [2].

For the survey of potential applications with a view to their use in Air Power, the following connections will be the focus, categorized as "Ground Communication" (6 and 7), "Air-to-Ground and Air-to-Air Communication" (4), and "Space Communication" (2). Each of these situations presents specific challenges, but QKD-based communication, among other options evaluated for each segment, may be a viable solution for ensuring the security of communications under these conditions, since the security of communications would be guaranteed by the laws of physics [39].

4.1. Ground Communication

The categorization of ground communication encompasses the use of such technology between static or semi-static entities located on the ground and, usually, over long distances. The main benefit would be related to communication security. That said, the main alternative for establishing communication would be QKD.

To this end, there are mainly two methods for operating long-distance quantum communication networks: the optical fiber network and the free-space network. In the case of ground communication, optical fiber networks would be more beneficial, as they present a lower probability of decoherence and existing optical fiber can be used. Multi-fiber mode can also make communication more precise. However, QKD-based communication in its basic form is limited to a few hundred kilometers over optical fiber, and it is impossible, at least for now, to store quantum information and use the optical fiber at the same time [40].

As an example in the context of the Brazilian Air Force, the implementation of secure communication based on quantum communication could be carried out across all entities of the organizational structure that require the secure transit of information. This would include the General Directorate Body, the Higher Advisory Bodies, the Bodies for Direct and Immediate Assistance to the Commander, and the Sectoral Direction Bodies, as well as their subordinate units [41].

It should be noted that such action is consistent with what is set out in the Aeronautics Information and Communication Technology Master Plan (PDTIC), with regard to the responsibilities of the Aeronautics Command's Information Technology System, and its implementation in the context of Air Power employment would potentially yield, in terms of ground communication, the "Guarantee of information security, encompassing the integrity, confidentiality, availability, and non-repudiation of information" [42].

4.2. Air-to-Ground and Air-to-Air Communication

The air-to-ground and air-to-air communication scenario can be seen in the process of exchanging information and data between aircraft themselves and/or ground units. In this case, the focus can be on applications related to messages with a low information rate. To achieve these objectives, QKD-based communication is an alternative, as previously described. However, other possibilities can also be evaluated.

One possibility would be the use of a quantum network for secure direct communication (QSDC) between the actors involved. Using this approach, direct messages are encrypted into quantum data, taking advantage of security similar to that of QKD, but without the need for key distribution, eliminating other security vulnerabilities associated with key storage and ciphertext attacks. However, one obstacle is the low qubit rate, which limits transmission to simple messages only, rather than audiovisual data or complex telemetry. In such cases, the network could switch to the QKD protocol to distribute the key and the encrypted data via classical channels [43].

As an example in the context of the Brazilian Air Force, the deployment of a communication network along the lines described above would be essential for the cooperation and integration of Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance systems, as well as the precise synchronization of various data and actions across radars, electronic warfare devices, weapon systems, etc. This includes as actors the component bodies of the Defense Intelligence System (SINDE), the Brazilian Airspace Control System (SISCEAB), the Brazilian Aerospace Defense System (SISDABRA), and the Integrated Border Monitoring System (SISFRON) [41].

4.3. Space Communication

Space communication refers to communication using satellites or in which one of the parties involved is located in space. As such, there is a need to develop a quantum communication network for long distances, greater than those of the previous categories.

The first potential application to be analyzed would be the determination of exact position through the implementation of a quantum network with clock synchronization, which would be a hybrid form of communication. In this scenario, communication would make use of GNSS satellites, but without concern for spoofing and interference. This would be made possible through the synchronization of independent clocks, especially atomic clocks (used in GNSS satellites) and local digital clocks. With perfectly synchronized clocks, precision would become arbitrarily high [44].

Another potential application of satellite-based quantum communication is related to its key role in establishing a quantum *internet* network in the future. A new necessary military capability will be the technology to detect other satellites, space objects, and space debris, and to track them. In this regard, although secure communication via satellites has already been demonstrated [45], a constellation of satellites equipped with entanglement sources and quantum memories will be needed to create dynamically configurable multi-link connections between any two points on Earth [19].

In the context of application within the Armed Forces, space-based quantum communication could be used within the scope of the Military Satellite Communications System (SISCOMIS), which is the main instrument for strategic communications enabling interoperability among the Armed Forces. Within the scope of SISCOMIS is the Geostationary Defense and Strategic Communications Satellite (SGDC) project, which will enable the expansion of the National Broadband Program (PNBL), in addition to the use of the exclusively military X Band, which will serve to increase the possibilities for reliable and secure communications of the Military Command and Control System — SISMC² [41].

The potential return of space communication in a scenario involving the employment of Air Power converges toward improving the secure acquisition of exact position accuracy, which is crucial in military missions, such as locating friendly aircraft, guiding precision munitions, and operating autonomous vehicles [2]. In other words, there would be an advance in the use of satellites for navigation, mapping, communication, and surveillance [46]. Such action is of paramount importance for the development of an Aerospace Force in an environment in which space is becoming increasingly weaponized [47].

5. Conclusion

Quantum communication represents a promising research area, both theoretically and practically, which has attracted great interest across various sectors. Based on the principles of Quantum Mechanics, quantum communication makes it possible to transmit information securely and in a way that is practically impossible to intercept without being detected. This characteristic makes it an attractive option for ensuring information security in military contexts.

The analysis of the evolution of quantum communication in the global, European, American, and Chinese scenarios shows that China has been a leader in research and development in this field, making significant advances and establishing large-scale quantum communication networks. The United States and Europe are also investing in research and initiatives to maintain their competitiveness and leadership in this field.

Regarding military applications, it can be seen that the development and implementation of quantum communication technologies has a broad impact on various areas, including Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance, given that security and encryption protocols are viable [48].

Within the scope of Air Power employment, quantum communication presents potential applications in different scenarios, including ground, air-to-ground, air-to-air, and space communication. Communication security is essential for the coordination and integration of air operations, and quantum communication can provide a reliable and secure solution to ensure the protection of sensitive information. In the context of the Brazilian Air Force, the implementation of quantum technologies, including quantum communication, aligns with the National Defense Strategy.

However, technological challenges still need to be overcome in order to advance the large-scale implementation of quantum communication. Mitigating noise and external interference in quantum emitters and receivers is one of the main obstacles to be faced. In addition, it is necessary to extend the range of quantum communication and increase its transmission rate to make it compatible with existing classical protocols.

Therefore, quantum communication has great potential to transform the communication capabilities of the Brazilian Air Force and other military bodies, providing greater security and efficiency in operations. Continuous investment in research and development in this field is essential to fully explore the potential of this technology and strengthen national security in the context of cyber warfare and military communications.

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