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Satellite-Based Quantum Key Distribution for Remote Secure Communication

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ABSTRACT
The background of this research focuses on the challenges of remote communication security in the ever-evolving digital era. Satellite-based Quantum Key Distribution (QKD) was chosen as a solution to address security concerns by utilizing the principles of quantum mechanics. The purpose of this study is to evaluate the effectiveness of satellite-based QKD in dealing with atmospheric disturbances and to identify factors that affect the performance of the system under varying weather conditions. The method used is a field experiment by transmitting quantum photons through satellites under various weather conditions and measuring the success rate of signal transmission. The results show that the influence of weather, especially rain and thick clouds, can reduce the success of signal transmission by up to 50%. However, in sunny weather conditions, the success rate reaches 95%. The conclusion of this study is that although satellite-based QKD promises secure communication solutions, atmospheric challenges are still a major obstacle, requiring further development in protocols and technologies to overcome such interference. This research makes an important contribution to the development of satellite-based QKD for safer global communication.

Keywords: *Communication Security, Quantum Key, Quantum Mechanics*

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INTRODUCTION

Communication security in the digital world is increasingly becoming a major concern in the midst of the rapid development of information and communication technology (Das, 2021). Various efforts have been made to ensure that data transmitted through the network remains safe from potential threats, both from outsiders who intend to hack and from other system disturbances. One promising approach to meeting this challenge is Quantum Key Distribution (QKD), a cryptographic technology that leverages the fundamental principles of quantum mechanics to ensure security in the exchange of encryption keys between the sender and receiver (Chen, 2021).

Quantum mechanics, with its unique properties such as superposition and entanglement, allows for methods that are almost impossible to hijack undetected (Wang, 2022). By taking advantage of this phenomenon, QKD offers a solution where any attempt to interrupt or spy on communications will cause an immediate detectable jam. The basic concept of QKD is the use of light particles or photons that are transmitted between two parties who want to communicate to share an encryption key that can only be used by both (R. Liu, 2022).

However, the implementation of QKD faces significant geographical limitations. Communication over fiber optic cables, although efficient over short distances, becomes impractical for long-distance communication, in particular for connecting very distant locations such as between continents or even between countries (Guo, 2021). Therefore, efforts to expand the range of QKD through satellite infrastructure have been the focus of intensive research in recent years. Satellites can provide a wider range of communication paths and allow the distribution of quantum keys without being hindered by the physical limitations faced by optical cables (W. Z. Liu, 2022).

Satellites, with their ability to transmit signals over a wide area, are able to reach areas that were previously difficult for traditional communication systems to reach (Currás-Lorenzo, 2021). This opens up the possibility to implement QKD on a global level, connecting various points around the world without the need for expensive and complicated cable infrastructure. Recent research shows that the use of satellites for quantum key distribution can be a very potential solution to improve the security of long-distance communications, even on an international scale (Cao, 2022).

A number of experiments have been carried out to test the feasibility of satellite-based QKD. For example, the Chinese satellite experiment project, Micius, which successfully demonstrated quantum communication via satellites at very long distances (Fan-Yuan, 2022). This achievement demonstrates the great potential of satellite-based QKD for use in secure global communications. However, there are still technical challenges that need to be overcome, such as signal stability issues, interference, and the need for more sophisticated devices to process and encrypt large quantities of quantum keys (Langenfeld, 2021).

As one of the revolutionary steps in the world of communication, satellite-based Quantum Key Distribution opens up great opportunities to present a more secure communication system in the future (Basset, 2021). The implementation of this technology is expected to overcome the problems that exist in conventional communication systems, while taking advantage of the great potential possessed by quantum and satellite technologies to create systems that are not only more efficient but also safer in the face of increasingly complex cyber threats (J. P. Chen, 2022).

There are still many technical challenges that must be overcome in the application of satellite-based Quantum Key Distribution (QKD), especially related to signal quality and communication stability (Cao, 2021). The QKD system is highly dependent on the ideal conditions of the communication channel, but in space, influences from the atmosphere and external interference can affect signal transmission. What's more, although satellite technology offers global coverage, major challenges remain in achieving stable communication and avoiding interference that can interfere with quantum data transmission over long distances (Woodward, 2021).

Limitations in satellite infrastructure are also an obstacle. Currently, the satellite used for the QKD experiment is still in the testing stage and has limited capacity (Matsuura, 2021). As the need for global secure communication increases, no system has been able to consistently provide a high level of reliability of quantum key distribution around the world. In this case, the gap is how to develop a more advanced satellite infrastructure to support wider and more effective QKD communication (Dequal, 2021).

In addition, the protocols and algorithms used in satellite-based QKD are still not fully mature to be implemented on a large scale (Nadlinger, 2022). Some experiments have shown that a well-functioning QKD system at close range may not necessarily work effectively at long distances, especially in environments affected by physical variables such as atmosphere or signal interference. There needs to be more research on the development of a more efficient and tamper-resistant QKD protocol (Gu, 2022).

Another factor that is still uncertain is the issue of cost and operational efficiency. Satellite and QKD technology requires enormous investments, both in terms of satellite launches and in the development of hardware and software that can handle the distribution of quantum keys effectively (Tian, 2022). The application of this technology on a commercial or government scale is still limited to large projects that require financial support and very expensive infrastructure. Therefore, another challenge is how to lower the cost to make it more affordable (B. Liu, 2022).

Another aspect that still needs to be solved is the compatibility between QKD and traditional communication systems (Yin, 2022). Satellite-based QKDs must be able to integrate with existing communication systems to ensure that data sent over conventional communication channels remains secure. The integration between quantum technology and conventional communication technology is one of the major gaps that need to be overcome to support the widespread adoption of satellite-based QKD (Sengan, 2022).

Filling this gap is critical to realizing a more secure global communication system, especially amid increasing threats to data privacy and security (Zhang, 2021). By overcoming the limitations that exist in the distribution of satellite-based quantum keys, we can create a communication infrastructure that is more resilient to interference and potential cyber attacks. Strengthening communication networks using satellite-based QKD technology allows for the creation of systems that are not only secure but also reliable on a large scale (L. Chen, 2022).

This research aims to develop a more efficient solution that can be widely applied in the use of satellite-based QKD for long-distance communication. By filling the gaps, we can create a system that is more affordable and accessible to various sectors, including the government and industrial sectors. The use of satellites as a quantum key distribution infrastructure will also pave the way for secure communication without geographical boundaries, expanding its application worldwide.

The proposed hypothesis is that with more advanced satellite technology and more efficient QKD protocols, long-distance communication can be carried out with a much higher level of security. Reducing interference, improving signal stability, and integrating these systems with existing technologies will improve the efficiency and effectiveness of satellite-based QKDs, providing long-term benefits in creating a secure and unshakable communication system (Wazid, 2021).

RESEARCH METHODS

This study uses an experimental design to test the application of satellite-based Quantum Key Distribution (QKD) in long-distance secure communication (Mahendran et al., 2022). This study is designed to identify and analyze the factors that affect the performance of quantum key distribution through satellites. The main focus of this experiment is to measure the effectiveness of the QKD protocol under conditions influenced by the atmosphere and other external factors that can affect signal quality, such as interference. In addition, this research also seeks to develop an algorithm that can optimize the distribution of quantum keys through satellite paths on a global scale (Jiulin et al., 2021).

The population in this study includes communication systems that use satellite and QKD technology for quantum key distribution. The research sample consists of several test satellites that have been launched and quantum communication systems used in global experiments, such as China's Micius project. The sample also includes the hardware and software used to implement the QKD protocol. The data collected will include the results of experiments conducted at various locations to test the distribution of quantum keys in various atmospheric conditions and external disturbances (Han et al., 2022).

The instruments used in this study include optical devices to transmit quantum photons via satellites, photon detection systems to measure the success of signal transmission, and hardware used to implement QKD. In addition, the software used for the analysis of experimental data is also very important for monitoring signal stability and detecting interference or eavesdropping on communications. Another instrument needed is a device to simulate atmospheric influences and signal interference, in order to measure their impact on the effectiveness of satellite-based QKD (Ji et al., 2021).

The first step in the research procedure is the selection of suitable satellites and the arrangement of QKD communication devices for data transmission. Once the system is set up, a series of tests are carried out by sending quantum keys via satellite to measure the quality of transmission under various atmospheric conditions. Each key conversation or exchange between the sender and receiver will be analyzed to evaluate the success rate of key distribution and tamper detection. Furthermore, the data collected will be analyzed using software to identify factors that affect the stability and efficiency of the system. This study will also evaluate the effectiveness of the algorithm developed to improve the performance of satellite-based QKD, with a comparison to conventional communication systems (Gill, 2020).

RESULTS AND DISCUSSION

The data used in this study came from quantum key distribution experiments using satellites, which were carried out in several field tests. The following table illustrates the results of a test involving the transmission of photons via satellite with various atmospheric conditions and the effects of signal interference. The data showed the results of the success rate of signal transmission for each test, both conducted at night with sunny weather and in adverse weather conditions such as rain and thick clouds. Measurements are made in specific units of time (e.g., in an hour) with the number of photons successfully detected.

Weather Conditions	Transmission Success (%)	Number of Photons Sent	Number of Photons Detected
Weather	95%	10.000	9.500
Thick Clouds	85%	10.000	8.500
Light Rain	75%	10.000	7.500
Heavy Rain	50%	10.000	5.000

This test provides a preliminary overview of the influence of weather on the success of satellite-based QKD signal transmission.

From the data obtained, it can be seen that weather conditions greatly affect the success rate of signal transmission. In clear weather conditions, the transmission success rate reaches 95%, which indicates that photons can pass through the atmosphere with little interference. However, when the weather changes for the worse, such as in thick cloud conditions or light rain, the transmission success rate decreases significantly, to 85% and 75%, respectively. This decline is caused by the scattering and absorption of photons by water particles and vapor in the atmosphere.

The transmission success in heavy rain conditions, which is only 50%, indicates that more extreme atmospheric disturbances can lead to a drastic decrease in the effectiveness of quantum key distribution. This shows the importance of addressing atmospheric influences in the design of satellite-based QKD systems. Factors such as cloud depth, humidity, and rain intensity have a major impact on the stability of signal transmission, which poses a major challenge in the application of this technology.

Overall, these data show that weather is an important variable that must be taken into account in satellite-based QKD systems, and make it clear that the success of quantum key transmission is highly dependent on the physical conditions of the atmosphere along the photon transmission path.

The next data is related to testing the stability of the QKD signal in transmitting quantum keys over very long distances, using satellites that have a certain capacity. The test was carried out at various distances, ranging from 500 km to 1,500 km, to measure the impact of distance on the quality of the distribution of quantum keys. In each test, the photons transmitted through the satellite and received by the receiver are analyzed to find out the number of photons successfully detected and the successful delivery of the quantum key.

Distance (km)	Transmission (%)	Success Number of Photons Sent	Number of Photons Detected
500 km	92%	10.000	9.200
1,000 km	89%	10.000	8.900
1,500 km	82%	10.000	8.200

This data shows a decrease in the transmission success rate as the distance between the sender and receiver increases.

The decrease in transmission success with increasing distance is an expected phenomenon in satellite-based QKD testing. The farther a quantum photon travels, the more likely it is that the photon is inhibited or distorted by particles and gases in the atmosphere. This is especially evident in tests conducted at a distance of 1,500 km, where the transmission success rate decreased to 82%.

This phenomenon is related to the basic principle of quantum mechanics, where photons sent through longer channels will experience a decrease in signal quality due to interactions with the environment, such as scattering or absorption by molecules in the air. Nevertheless, the data show that despite the decline, satellite-based QKD systems still show quite good results at long distances, which is an important indicator for the continuation of research in extending the reach of this technology.

In addition, the decline also suggests that the successful transmission of quantum keys over longer distances requires additional solutions, such as the use of quantum repeaters or photon encoding optimization, to overcome this distance problem.

The data obtained from weather and distance testing showed a strong relationship between external factors and the success of satellite-based QKD transmission. In adverse weather conditions and longer distances, there is a significant decrease in the transmission success rate. This creates a direct relationship between atmospheric stability and signal transmission quality, which affects the effectiveness of the distribution of quantum keys. This data provides insight into the need for the development of systems that can address these challenges.

The correlation between weather, distance, and transmission success provides a basis for researchers to design more efficient satellite-based QKD systems. In this case, the influence of weather and distance must be taken into account to ensure that the distribution of quantum keys can run smoothly despite atmospheric disturbances or long distances. More research is needed to explore new technologies that can mitigate these impacts.

Overall, this data reveals that despite the significant influence of weather and distance on satellite-based QKD systems, the technology still has great potential for use in long-distance secure communications, noting that there needs to be further optimization in system design and infrastructure.

A case study was conducted on a quantum key distribution test using the Micius satellite that successfully transmitted photons at a distance of 1,200 km between China and the Space Station. The resulting data show that at such distances, the distribution of quantum keys remains successful despite variations in atmospheric conditions. During the experiment, the system managed to maintain a key transmission success rate of about 87%, although at some point it experienced minor disturbances caused by atmospheric factors such as thick clouds.

These results show that despite the interference in transmission, experiments using satellites can still be carried out with a high success rate. This success is important in testing the potential of satellite-based QKD applications on a larger scale and at longer distances. These tests also show that satellite-based QKD technology is able to survive in sub-ideal conditions and can still be used for secure communication.

This research provides important data that shows the great potential of the use of satellites in quantum key distribution. The success of the system despite less favorable atmospheric conditions suggests that this technology can be further developed to meet the needs of global secure communications in the future.

This study shows that satellite-based quantum key distribution can be carried out with a high success rate in sunny weather conditions, but has a significant decrease in severe weather conditions, such as rain or thick clouds. Experimental data showed that the success rate of quantum photon transmission reached 95% in sunny weather, while in heavy rain conditions, the success rate decreased by up to 50%. The influence of the atmosphere on the success of transmission is the main factor that affects the performance of satellite-based QKD systems. In addition, testing shows that longer transmission distances also decrease the effectiveness of key distribution, although it is still within acceptable ranges.

The results of this study are consistent with several previous studies that show that the distribution of quantum keys through satellites can be affected by atmospheric conditions. Previous research, such as the one conducted by the Chinese team in the Micius experiment, also identified challenges in overcoming atmospheric disturbances, especially at longer distances (Vishwakarma, 2022). However, this study is more in-depth in measuring the influence of weather on satellite-based QKD systems at various distances and conditions. The main differences of this study are the emphasis on the relationship between weather conditions and quantum signal transmission performance, as well as the need for special protocols that can optimize QKD systems in unstable atmospheric conditions (Khan, 2022).

The results of this study indicate that although satellite-based QKD technology offers great potential for secure communication over long distances, there are still challenges that need to be overcome to ensure its reliability on a global scale (Almaiah, 2022). The significant decrease in the transmission success rate in adverse weather conditions suggests that atmospheric influences should be a major concern in the development of satellite-based QKD systems. It is also a sign that while this technology is promising, more advanced infrastructure and protocols are needed to improve the stability and resilience of the system to external interference (Yerrapragada, 2021).

The implication of the results of this study is the importance of developing technologies and algorithms that can overcome atmospheric disturbances in satellite-based

QKD systems (Lee, 2022). Knowing that weather conditions can significantly affect system performance, solutions such as the development of satellites with more advanced signal processing capabilities or the use of more efficient coding techniques are crucial. In addition, the study indicates that secure communication over long distances via satellite requires a more holistic approach, including real-time monitoring of atmospheric conditions and dynamic system adjustments to mitigate the negative impacts of weather disturbances (Sanchez, 2021).

The results of this study are influenced by the main factor, namely the physical characteristics of the atmosphere that can affect the transmission of quantum photons (Olovsson, 2022). Quantum photons are particularly susceptible to scattering and absorption by particles in the atmosphere, such as water vapor and clouds, which causes a decrease in the signal received by the receiver. Rain, thick clouds, and even atmospheric pollution can block the transmission path, reducing the number of photons that reach their destination. Over longer distances, more photons are lost or inhibited by these factors, thus reducing the effectiveness of the quantum key distribution (Pirandola, 2021).

The next step is to develop more advanced satellite technology and QKD protocols that are more resistant to atmospheric disturbances. Further research should focus on optimizing hardware that can detect and address atmospheric problems in real-time, as well as developing algorithms capable of adapting key distribution processes to changing weather conditions (Nguyen, 2021). In addition, further experiments need to be carried out in various locations and geographical conditions to get a more complete picture of the impact of the atmosphere on the distribution of quantum keys. Given the great potential of this technology, international collaboration to improve satellite infrastructure and quantum communication systems is also an important step in accelerating the global adoption of satellite-based QKD (Tedeschi, 2022).

CONCLUSION

The study revealed that the influence of weather, especially poor atmospheric conditions, can significantly reduce the success rate of quantum photon transmission in satellite-based QKD systems. Although previous studies have also noted atmospheric influences, these findings go deeper in identifying variations in the success of photon transmission under various weather conditions and transmission distances, which is a major factor that needs to be addressed in the development of this technology.

A major contribution of this study is a deeper understanding of how weather and atmospheric conditions affect the performance of satellite-based QKDs. The research also provides new insights into the need to develop specific algorithms and protocols to address atmospheric disturbances, as well as the importance of systems that can adapt to dynamic weather conditions. The concepts and methods developed in this study are expected to accelerate the adoption of satellite-based QKD in the future.

The limitations of this study lie in the testing that is only carried out in certain weather conditions and within a limited transmission distance. Further research is needed to test satellite-based QKD systems in a variety of geographic and more diverse weather conditions, as well as to develop new technologies that can reduce the impact of atmospheric disturbances. The direction of further research should focus on satellite hardware innovation and the development of protocols that can improve the stability of quantum photon transmission over longer distances.

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