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HOW MAY SIGNAL LOSS BE DECREASED AND ENCRYPTION IMPROVED BY QUANTUM ENTANGLEMENT IN SATELLITE COMMUNICATION

Abstract: *Satellite communication is a critical component of global connectivity, enabling data transmission across vast distances for applications such as telecommunications, navigation, and broadcasting. However, signal degradation due to atmospheric interference, scattering, and attenuation presents a significant challenge to maintaining reliable communication. This study explores the role of quantum entanglement in mitigating signal loss and improving encryption in satellite communication systems. By leveraging quantum key distribution (QKD) and quantum error correction techniques, secure and efficient data transmission can be achieved. Various strategies, including adaptive beamforming, higher frequency bands, satellite relays, and real-time atmospheric monitoring, are examined to enhance communication reliability. The integration of quantum communication with advanced signal processing techniques demonstrates potential* *improvements in data integrity, reduced latency, and enhanced security. Furthermore, the study investigates the impact of deploying higher frequency bands and optimizing transmission through real-time atmospheric monitoring to counteract signal attenuation. The findings highlight the transformative potential of quantum technology in modern satellite networks, offering a pathway to the next generation of secure and efficient communication. While challenges such as atmospheric disturbances and technical complexities remain, continued advancements in quantum technologies and real-time optimization strategies hold promise for overcoming these obstacles. Future research should focus on refining quantum protocols and addressing implementation challenges to fully realize the benefits of quantum entanglement in satellite communication systems.*

Key words: *communication signals, atmospheric interference, quantum communication, prediction models, signal degradation, error correction.*

Introduction

Communication signals are essential for transmitting information across vast distances, enabling global connectivity in various fields such as telecommunications, satellite navigation, broadcasting, and the internet [1, 2]. They facilitate real-time communication between individuals, businesses, and governments, ensuring the smooth exchange of data, voice, and multimedia content. In critical sectors like aviation, defense, and emergency response, reliable communication signals play a vital role in coordinating operations and ensuring safety [3-5]. Advances in signal transmission technology have revolutionized industries, enhancing efficiency, security, and accessibility in modern society. Without strong and stable communication signals, global infrastructure, economic activities, and everyday interactions would be significantly disrupted.

Communication signals degrade over long distances due to atmospheric interference, scattering, and attenuation. Atmospheric interference occurs due to weather conditions such as rain, snow, fog, and humidity, which absorb and scatter signals, leading to degradation (known as rain fade) [6,7]. Additionally, disturbances in the ionosphere, influenced by solar activity, can cause signal refraction and dispersion, especially at lower frequencies [8]. The troposphere also contributes to interference through temperature and pressure variations, leading to signal bending and turbulence [9]. Scattering occurs when signals interact with atmospheric particles, causing redirection and loss of strength. Rayleigh scattering happens when the signal's wavelength is much larger than air molecules, resulting in weak but widespread dispersion [10]. Mie scattering occurs when signal wavelengths are comparable to water droplets or dust, leading to stronger disruption [11]. Non-selective scattering, caused by larger particles like clouds and aerosols, uniformly scatters signals in all directions, further weakening their intensity. Attenuation refers to the gradual weakening of signals as they travel through the atmosphere. This is primarily due to absorption by atmospheric gases like water vapor and oxygen, which affect microwave and infrared frequencies[12]. Additionally, free-space path loss occurs as signals spread out over long distances, naturally reducing their power. Multipath effects, where signals reflect off surfaces such as buildings or mountains, can distort and weaken transmissions. These factors lead to reduced signal strength, increased bit error rates, and loss of quantum entanglement, as well as signal fading, disruptions, and higher latency. Increased energy consumption and limited performance of free-space optical and quantum communication further impact efficiency [13-15]. Ultimately, these challenges result in compromised data integrity, higher operational costs, and reduced feasibility of secure and long-distance transmissions.

To mitigate signal degradation in satellite communication, several strategies can be employed, including adaptive beamforming, error correction techniques, using higher frequency bands, deploying satellite relays and quantum repeaters, and utilizing weather prediction models and real-time atmospheric monitoring to make proactive adjustments in transmission parameters, reducing disruptions caused by adverse conditions. These combined approaches enhance the resilience and efficiency of satellite-based communication networks.

Methods

To address signal degradation and enhance encryption in satellite communication through quantum entanglement, a multifaceted approach was employed. The study integrates quantum key distribution (QKD), quantum error correction, and advanced signal processing techniques to improve data integrity and transmission efficiency. QKD protocols, such as BB84 and E91, were analyzed for their effectiveness in secure key exchange, while error correction methods, including Shor’s code and surface codes, were examined to mitigate quantum decoherence and noise. A novel adaptive beamformer, designed using the minimum variance distortionless response (MVDR) criterion combined with kernel techniques, enhances signal quality by dynamically adjusting the phase and amplitude of multiple antenna elements. The performance of higher frequency bands, such as Ka-band (26-40 GHz) and optical wavelengths, was assessed to minimize atmospheric interference, while satellite relays were deployed to extend signal reach and reduce degradation through inter-satellite laser communication and AI-driven signal processing. Additionally, real-time atmospheric monitoring and prediction models were utilized to predict disturbances like rain fade and ionospheric turbulence, allowing for proactive transmission adjustments. By leveraging quantum entanglement and advanced signal processing, this study aims to enhance satellite communication reliability, reduce latency, and strengthen encryption, paving the way for the next generation of secure global communication networks.

Discussion and Results

Mitigation Strategies for Signal Degradation in Satellite Communication

Adaptive beamforming

Adaptive beamforming is a signal processing technique that optimizes the direction and strength of transmitted or received signals by dynamically adjusting the phase and amplitude of multiple antenna elements. It helps improve signal quality by focusing energy toward the intended receiver while minimizing interference from other sources. This technique is widely used in satellite communication, 5G networks, radar systems, and quantum communication to enhance signal clarity, increase efficiency, and reduce power consumption [16]. By continuously monitoring the signal environment and making real-time adjustments, adaptive beamforming ensures reliable data transmission even in challenging conditions such as atmospheric interference or multipath effects. Its ability to provide high-precision directional communication makes it essential for secure and high-performance wireless networks. A novel adaptive beamformer is designed using the minimum variance distortionless response (MVDR) criterion combined with kernel techniques. This approach requires inverting a low-dimensional Gram matrix rather than a high-dimensional sample covariance matrix, greatly reducing computational complexity [17]. Compared to single-constraint adaptive beamforming, multi-constraint adaptive beamforming offers greater adaptability to varying environments. However, the multi-point optimal and precise array response control (MOPARC) method, despite being an effective multi-constraint approach, is sensitive to the presence of the desired signal. To enhance the robustness of multi-constraint adaptive beamforming, we introduce a novel algorithm that integrates the MOPARC method with interference-plus-noise covariance matrix (INCM) reconstruction [18]. A sparsity-based adaptive beamforming (ABF) approach is proposed for efficiently processing coherent signals using polarized sensor arrays (PSA). By reorganizing the data, this method leverages the spatial sparsity of observed signals, converting it into row-sparsity within a waveform-polarization composite matrix [19]. Adaptive beamforming methods have suffered significant performance degradation when even small discrepancies have existed between the actual and assumed array responses to the desired signal. These mismatches have frequently occurred in practical scenarios due to violations of fundamental assumptions about the environment, signal sources, or sensor arrays. This issue has been particularly critical when the beamformer's training data snapshots have contained desired signal components, making the adaptive array highly sensitive to model inaccuracies and array imperfections. Even when the array response to the desired signal has been precisely known, performance degradation has still occurred if the number of training samples has been too small. To address these challenges, a novel approach is introduced to robust adaptive beamforming, which has been capable of handling unknown mismatches of any type in the array response of the desired signal. This method has been developed for the most general case, accommodating an arbitrary-dimensional desired signal subspace, making it applicable to both rank-one (point source) and higher-rank (scattered source or fluctuating wavefront) models [20, 21].

Error correction techniques

Error correction techniques are essential in communication systems to detect and correct errors that occur during data transmission, ensuring accurate and reliable communication. These techniques are particularly important in satellite communication, where signals are affected by atmospheric interference, scattering, and attenuation [22]. One common method is Forward Error Correction (FEC), which adds redundancy to transmitted data, allowing the receiver to detect and correct errors without requiring retransmission. Techniques such as Hamming codes, Reed-Solomon codes, and Low-Density Parity-Check (LDPC) codes are widely used in satellite links and deep-space communication [23-25]. Another approach is Automatic Repeat Request (ARQ), which relies on acknowledgments and retransmissions. If an error is detected, the receiver requests the sender to resend the corrupted data, ensuring data integrity. A more advanced method, Hybrid ARQ (HARQ), combines FEC and ARQ, correcting minor errors through FEC while requesting retransmission for more severe errors [26]. This approach enhances efficiency and is commonly used in modern communication networks, including 4G, 5G, and satellite systems. In quantum communication, Quantum Error Correction (QEC) is used to protect quantum information from decoherence and noise. Quantum codes, such as Shor's code and Surface codes, enable the detection and correction of errors in entangled qubits, making them essential for secure quantum key distribution (QKD) in satellite-based quantum networks [27, 28]. Error correction techniques play a crucial role in maintaining data integrity, reducing signal degradation, and improving communication efficiency in satellite systems. By minimizing transmission errors and ensuring reliable data exchange, these methods contribute to the development of more robust and secure communication networks.

Using higher frequency bands

Using higher frequency bands is an effective strategy to improve satellite communication by reducing signal degradation caused by atmospheric interference, scattering, and attenuation. Higher frequency bands, such as the Ka-band (26-40 GHz) and optical wavelengths (infrared and visible light), offer several advantages over lower frequency bands like C-band (4-8 GHz) and Ku-band (12-18 GHz) [29]. One major benefit of higher frequency bands is their increased data transmission capacity. Higher frequencies allow for wider bandwidths, enabling faster data rates and more efficient communication, which is essential for applications like high-speed internet, 5G networks, and advanced satellite broadcasting. Additionally, signals in these bands experience less congestion, as lower frequency bands are often overcrowded due to extensive use in telecommunications and broadcasting [30,31]. Despite these advantages, higher frequency bands are more susceptible to atmospheric absorption, particularly due to rain, humidity, and cloud cover, leading to a phenomenon known as rain fade [32]. To mitigate this issue, techniques such as adaptive beamforming, site diversity, and error correction protocols are implemented to maintain stable signal quality. Optical communication, which operates in even higher frequency ranges, can bypass many traditional interference problems but requires precise alignment between satellites and ground stations [33]. In summary, using higher frequency bands enhances data capacity and reduces congestion in satellite communication. However, their increased sensitivity to atmospheric conditions requires advanced signal processing and mitigation strategies to ensure reliable and efficient transmission.

Deploying satellite relays

Deploying satellite relays is a crucial strategy for improving long-distance communication by extending signal reach and minimizing degradation. In satellite communication, direct transmission over vast distances can lead to signal loss due to free-space path loss, atmospheric interference, and scattering. Satellite relays help overcome these challenges by acting as intermediate nodes that receive, amplify, and retransmit signals to their intended destinations. One of the main advantages of satellite relays is enhanced coverage, allowing signals to be transmitted over longer distances without significant loss. This is especially beneficial for global broadband services, intercontinental data transmission, and space exploration missions [34]. Additionally, relays improve communication reliability by reducing latency and maintaining stronger signals in areas where direct transmission would be inefficient or impossible. Satellite relays are essential in multi-satellite constellations, such as the Starlink and OneWeb networks, which provide continuous global coverage by forming interconnected satellite links. In quantum communication, relay satellites play a key role in distributing entangled photon pairs over long distances, enabling secure quantum key distribution (QKD) [35]. Despite their advantages, deploying satellite relays comes with challenges, including higher costs, increased complexity, and potential signal delays. However, advancements in inter-satellite laser communication, AI-driven signal processing, and autonomous satellite networks are helping to optimize relay efficiency [36, 37]. In summary, deploying satellite relays significantly enhances signal reach, communication reliability, and global connectivity, making them essential for modern telecommunications, deep-space missions, and secure quantum networks.

Weather prediction models and real-time atmospheric monitoring

Weather prediction models and real-time atmospheric monitoring play a crucial role in maintaining reliable satellite communication by helping mitigate signal degradation caused by atmospheric interference. Weather prediction models use advanced algorithms, satellite observations, and meteorological data to forecast atmospheric conditions such as rain, humidity, fog, and solar activity, which can affect signal propagation [38]. By anticipating adverse weather conditions, communication networks can implement proactive measures, such as adjusting transmission power, switching frequency bands, or rerouting signals through alternative satellites. Real-time atmospheric monitoring provides continuous updates on atmospheric turbulence, ionospheric disturbances, and cloud cover, allowing for immediate adjustments in satellite operations. For example, in Ka-band and optical communication, where signals are highly susceptible to rain fade and cloud cover, real-time monitoring helps optimize data transmission by dynamically adjusting beam direction or applying error correction techniques [39]. Additionally, [40]. This approach is especially beneficial for military communications, remote sensing, and global broadband services, where uninterrupted connectivity is critical.

Conclusion

The integration of quantum entanglement into satellite communication presents a promising solution to signal degradation and security vulnerabilities. By employing quantum key distribution and error correction methods, secure transmission with reduced signal loss becomes feasible. Adaptive beamforming, higher frequency bands, and satellite relays further strengthen communication reliability. While challenges such as atmospheric interference and technical complexity persist, advancements in quantum technologies and real-time monitoring approaches can significantly enhance efficiency. This study underscores the potential of quantum entanglement to revolutionize satellite communication, ensuring robust and secure global connectivity. Future research should focus on optimizing quantum protocols and overcoming practical implementation barriers to maximize the benefits of this emerging technology.

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СПУТНИКТІК БАЙЛАНЫСТАҒЫ КВАНТТЫҚ ШАТАСУ АРҚЫЛЫ СИГНАЛДЫҢ ЖОҒАЛУЫН ҚАЛАЙ АЗАЙТУҒА ЖӘНЕ ШИФРЛАУДЫ ЖАҚСАРТУҒА БОЛАДЫ

Спутниктік байланыс – телекоммуникация, навигация және хабар тарату сияқты қосымшалар үшін деректерді алыс қашықтыққа жіберуге мүмкіндік беретін жаһандық байланыстың маңызды құрамдас бөлігі. Алайда, атмосфералық кедергілер, шашырау және әлсіреу нәтижесінде сигналдың нашарлауы сенімді байланысты сақтауда елеулі қиындықтар тудырады. Бұл зерттеу спутниктік байланыс жүйелерінде сигнал жоғалуын азайту және шифрлауды жақсартуда кванттық шатасудың рөлін зерттейді. Кванттық кілттерді тарату (QKD) және кванттық қателерді түзету әдістерін қолдану арқылы қауіпсіз және тиімді деректерді тасымалдауға қол жеткізуге болады. Байланыстың сенімділігін арттыру үшін адаптивті сәулелік пішіндеу, жоғары жиілікті диапазондар, спутниктік релелер және нақты уақыттағы атмосфералық мониторинг сияқты әртүрлі стратегиялар қарастырылады. Кванттық байланысты озық сигналдарды өңдеу әдістерімен біріктіру деректердің тұтастығын жақсарту, кідірісті азайту және қауіпсіздікті арттыру мүмкіндігін көрсетеді. Сонымен қатар, зерттеу жоғары жиілікті диапазондарды пайдалану және нақты уақыт режиміндегі атмосфералық мониторинг арқылы сигнал әлсіреуіне қарсы күрес үшін берілімді оңтайландыру әсерін зерттейді. Алынған нәтижелер заманауи спутниктік желілерде кванттық технологияның трансформациялық әлеуетін көрсетеді, бұл келесі буынның қауіпсіз және тиімді байланысына жол ашады. Атмосфералық кедергілер мен техникалық күрделіліктер сияқты қиындықтар сақталғанымен, кванттық технологиялар мен нақты уақыттағы оңтайландыру стратегияларын одан әрі дамыту бұл кедергілерді жеңуге үміт береді. Болашақ зерттеулер кванттық протоколдарды жетілдіруге және спутниктік байланыс жүйелерінде кванттық шатасудың артықшылықтарын толық жүзеге асыру үшін енгізу мәселелерін шешуге бағытталуы керек.

Түйін сөздер: *коммуникациялық сигналдар, атмосфералық кедергілер, кванттық байланыс, болжау модельдері, сигналдың деградациясы, қателерді түзету.*

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КАК МОЖНО УМЕНЬШИТЬ ПОТЕРЮ СИГНАЛА И УЛУЧШИТЬ ШИФРОВАНИЕ С ПОМОЩЬЮ КВАНТОВОЙ ЗАПУТАННОСТИ В СПУТНИКОВОЙ СВЯЗИ

Спутниковая связь является важнейшим компонентом глобальной связи, обеспечивая передачу данных на большие расстояния для таких приложений, как телекоммуникации, навигация и радиовещание. Однако ухудшение сигнала из-за атмосферных помех, рассеяния и затухания создает значительные проблемы для поддержания надежной связи. В данном исследовании изучается роль квантовой запутанности в снижении потерь сигнала и повышении уровня шифрования в системах спутниковой связи. Использование квантового распределения ключей (QKD) и методов квантовой коррекции ошибок позволяет добиться безопасной и эффективной передачи данных. Рассматриваются различные стратегии, включая адаптивное формирование луча, более высокие частотные диапазоны, спутниковые ретрансляторы и мониторинг атмосферы в режиме реального времени, для повышения надежности связи. Интеграция квантовой связи с передовыми методами обработки сигналов демонстрирует потенциальные улучшения целостности данных, сокращение задержек и повышение безопасности. Кроме того, исследование рассматривает влияние использования более высоких частотных диапазонов и оптимизации передачи данных с помощью мониторинга атмосферы в режиме реального времени для противодействия затуханию сигнала. Полученные результаты подчеркивают преобразующий

потенциал квантовых технологий в современных спутниковых сетях, открывая путь к следующему поколению безопасной и эффективной связи. Хотя проблемы, такие как атмосферные возмущения и технические сложности, сохраняются, дальнейшее развитие квантовых технологий и стратегий оптимизации в реальном времени дает надежду на их преодоление. Будущие исследования должны быть сосредоточены на совершенствовании квантовых протоколов и решении проблем внедрения, чтобы в полной мере реализовать преимущества квантовой запутанности в системах спутниковой связи.

Ключевые слова: *коммуникационные сигналы, атмосферные помехи, квантовая связь, модели прогнозирования, деградация сигнала, исправление ошибок.*

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ПРИРОДНЫЕ МАТЕРИАЛЫ КАК НОВЫЕ ВЫСОКОТЕМПЕРАТУРНЫЕ ПОКРЫТИЯ

Аннотация: *Разработано оборудование полигона для исследования теплообмена в природных покрытиях. Создана поточная линия для нанесения покрытий. В качестве природных материалов выбраны кварциты, граниты и тешениты. Создан термоинструмент с детонационной струей и разработана технология получения порошков дроблением в замкнутом объёме. Горелка имеет автоматическое устройство для управления режимом работы. Порошки готовились в формах из эллиптических поверхностей с различным эксцентриситетом. Технология увеличивает выход порошка класса* $(0 \div 2) \times 10^{-3}$ *м и повышает степень упрочнения порошка. Автоматическое устройство устанавливает оптимальное расстояние до покрытия, формирует оптимальное пятно растекания струи. Технология предусматривает выброс воды на покрытие. Поперечная скорость участка воспламенения спинового детонационного факела определяется из наклона к образующей спирального следа. Имеет место стабилизация горения за счет торможения на покрытии. Исследования с помощью голографической интерферометрии показало, что оно полезно для прогнозирования разрушения покрытия. Покрытия с тремя тепловыми источниками представляет собой экран, поглощающий волны факела термоинструмента. Покрытие*