QUANTUM-AI INTEGRATION: A SYSTEMATIC REVIEW OF ALGORITHMS, HARDWARE EFFICIENCY AND SECURE APPLICATIONS

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ABSTRACT

Objective: This research aims to evaluate and synthesise the development of artificial intelligence (AI) technologies integrated with quantum computing, especially regarding processing efficiency, hardware energy efficiency, and digital communication security.

Research Design & Methods: This research utilizes the Systematic Literature Review (SLR) method of 13 scientific articles published in the ETRI Journal's 2024 special issue titled "Next-Gen AI and Quantum Technology." The literature was selected based on inclusion criteria that included relevance to quantum AI, presence of experimental data, and contribution to computational efficiency.

Findings: The study results show that approaches such as Quantum Reinforcement Learning and Quantum Kernel Classifiers can improve training efficiency and classification accuracy. Spiking Neural Networks technology reduced power consumption in AI-SoC and edge device designs. At the same time, the Quantum Key Distribution system demonstrated an error rate as low as 0.62% with WDM filter integration. The AONet video anomaly detection model achieves up to 97% AUC with the combination of a residual autoencoder and an attention module architecture.

Implications & Recommendations: These findings indicate that quantum AI has great potential to overcome the limitations of classical computing in real-time applications and large-scale systems. However, challenges related to quantum noise, hardware stability, and integration with classical systems still need to be addressed. This research recommends strengthening hybrid infrastructure, developing interoperability standards, and utilizing multi-core architectures to support processing efficiency and data security.

Contribution & Value Added: This study significantly contributes by systematically mapping existing methodologies and experiments in quantum AI, establishing a conceptual framework for future research avenues, and incorporating quantum AI technologies into industry, edge computing, and upcoming security systems.

Keywords: Edge Computing, Quantum-AI, Quantum Computing, Deep Learning.

JEL codes: O33, L86, D83
Article type: research paper

INTRODUCTION

The rapid advancement of digital technology in the industrial era 5.0 has brought new challenges and opportunities for various sectors, especially in computing and Artificial Intelligence (AI) (Pulicharla, 2023). The demand for fast, efficient, and secure data processing is driving the development of technologies that rely on conventional hardware but also utilize the extraordinary capabilities of quantum computing (Jindal, 2024). One of the cutting-edge approaches in this field is Hybrid Quantum-Classical Computing (HQCC), which combines the advantages of classical and quantum computing to tackle complex problems that cannot be solved with traditional approaches (Otterbach et al., 2017). HQCC has attracted significant attention from the scientific community due to its ability to accelerate the training of machine learning models, optimize algorithm performance, and reduce computing power consumption (Perelshtein et al., 2022).

The integration of AI with quantum computing in recent years has led to cutting-edge approaches such as Quantum Reinforcement Learning (QRL) and Quantum Kernel Classifiers, which offer high training efficiency and classification accuracy (Blank et al., 2020; Gilvarry and Emeakaroha, 2023; Jia et al., 2023). Meanwhile, hardware developments based on Spiking Neural Networks (SNN) bring highly relevant energy-efficient solutions for edge applications and IoT devices (Han et al., 2020; Venker et al., 2023). Quantum Key Distribution (QKD) technology also strengthens data security through a theoretically unhackable communication system (Diamanti, 2021). These approaches have been tested in real-world contexts and have shown superior performance in big data processing, real-time video monitoring, and adaptive classification systems (Li et al., 2023; Shah et al., 2023). The need for infrastructure that supports the inference of large-scale AI models, such as GPT-2 and other generative systems, also drives the exploration of new computing architecture designs (Gropp et al., 2020). Innovations such as PF-GEMV and XEM show that improving the efficiency of matrix-vector multiplication is key to improving the performance of next-generation AI systems (Wang et al., 2024). Furthermore, compiler development approaches such as NEST-C have also been an important breakthrough in reducing inference latency and increasing throughput (Park et al., 2024).

Quantum computing also opens a new era in cybersecurity by developing Quantum Key Distribution (QKD) (Gujar, 2024). This technology ensures secure data communication with very low error rates, as demonstrated by BB84-based QKD tests that achieved quantum bit error rates as low as 2.9% in 97 km transmissions using Wavelength Division Multiplexing (WDM) synchronization (Tanaka et al., 2008). Other research shows that using WDM filters in BB84-based QKD systems allows for more compact designs without internal alignment, making this technology even more practical to implement (Kim, Lim, et al., 2024). Meanwhile, in terms of security and surveillance applications, the integration of AI and quantum computing results in a system capable of detecting video anomalies in real-time with high accuracy, as demonstrated by the AONet architecture (Shah et al., 2023). Besides efficiency and security, the focus on sustainability is also taking center stage in developing AI systems. Using Spiking Neural Networks (SNN) to create power-efficient hardware is an attractive alternative for mobile and always-on applications (Chundi et al., 2021). Research shows that power consumption can be reduced to below 300 W when active, without compromising the predictive performance of the system (Venker et al., 2023).

This research aims to conduct a systematic literature review of recent technical contributions and experiments in quantum AI, based on 13 scientific articles published in the ETRI Journal 2024 special issue. With a focus on processing efficiency, information security, and system performance, this research presents a thematic analysis of developed quantum AI models, algorithms, and architectures. The findings are expected to strengthen scientific understanding and provide a theoretical and practical foundation for developing more adaptive, secure, and sustainable digital technologies in the future.

This chapter will be organized using a descriptive and exploratory approach. It will begin with a discussion of the basic theory and background of related technologies, followed by identification of each study's contribution, and ending with a mapping of strategic issues that can serve as a foothold for the development of further research and relevant technology policies. Thus, the results of this study are expected to make a real contribution to the development of science and information technology in a global context that increasingly demands efficiency, security, and sustainability.

LITERATURE REVIEW

Quantum computation

Quantum computing is a new paradigm based on the principles of quantum mechanics, such as superposition and entanglement, enabling faster data processing than classical computers. (Garewal et al., 2024). Qubits allow quantum computers to tackle complex problems in optimization, machine learning, and cybersecurity (Osaba et al., 2022). The technology is used in the financial and healthcare sectors for complex calculations such as financial risk modelling and molecular simulation (Adegbola et al., 2024). However, the implementation of quantum computing is still constrained by hardware limitations and quantum errors that require advanced correction techniques (Celsi and Celsi, 2024; Salam and Ilyas, 2024). A hybrid quantum-classical computing approach is applied as an interim solution to combine the advantages of classical and quantum computing in various applications, such as logistics and material modelling (Edwards et al., 2020). In the field of cybersecurity, quantum algorithms such as Shor's Algorithm can break classical encryption such as RSA quickly, but on the other hand, they also open up opportunities for the development of quantum cryptography, such as Quantum Key Distribution (QKD), which offers higher security (Ahmed et al., 2024). As the technology evolves, collaboration between academia, industry, and government is key to accelerating the adoption of quantum computing and mitigating its challenges.

Deep Learning Challenges

Deep learning uses artificial neural networks with multiple layers to automatically extract features from big data. While it excels in pattern recognition, NLP, and data-driven prediction, it faces major challenges of interpretability, big data requirements, and computational efficiency (Vebiyatama and Ernawati, 2024). One major obstacle is the reliance on large amounts of data to produce accurate predictions. However, the availability of large datasets is often a bottleneck, especially when the required data is challenging to obtain or poorly labeled (Miotto et al., 2018). Additionally, training deep learning models requires high computational power, mainly due to the complexity of the neural network architecture that requires large-scale parallel processing.

Another issue is model interpretability, which makes prediction results difficult to understand and explain. Deep learning models are often perceived as black boxes, which can decrease user confidence in critical applications such as health and finance (Ferreira et al., 2019). Some methods, such as explainable AI (XAI), are being developed to improve transparency, but they still have limitations. As a solution, blockchain integration is proposed to improve transparency and security in deep learning. Blockchain can record every change in the training process in a decentralized manner, improving the auditability and reliability of models in systems that require high security, such as finance and healthcare (Shafay et al., 2023). Innovations in model optimization, computational efficiency, and integration of new technologies are expected to overcome the challenges of deep learning, enabling wider adoption with more transparent and reliable performance.

METHODS

This research uses a qualitative-descriptive approach through a systematic literature review (SLR) method to gain a thorough understanding of the development of the integration of artificial intelligence (AI) and quantum computing, especially in the context of Hybrid Quantum-Classical Computing (HQCC), energy efficiency, and applications in security and surveillance systems. This study reviews and synthesizes research results from various sources to identify technology trends, innovative contributions, and open research gaps.

The primary data source was obtained from the 2024 special issue of the ETRI journal, which contains 13 articles related to quantum AI technology, including algorithm development, quantum communication systems, and power-efficient hardware based on Spiking Neural Networks (SNN). In addition, additional references came from reputable journals such as IEEE Transactions on Quantum Engineering, Nature Quantum Information, conference proceedings, and industry whitepapers. The selection process was conducted through literature searches on databases such as IEEE Xplore, SpringerLink, and ScienceDirect, with strict inclusion criteria to ensure the validity and relevance of the sources.

After data collection, a thematic classification into four main groups was conducted: Quantum-AI algorithms, computational system efficiency, quantum security, and intelligent surveillance. The analysis was conducted narratively and comparatively to evaluate each study's approaches, experimental results, and contributions. The synthesis results are presented as tables and diagram visualizations to clarify the comparison and interrelationships between findings. This research does not involve direct experimentation, but provides a strong conceptual basis for developing further applicable and experimental studies.

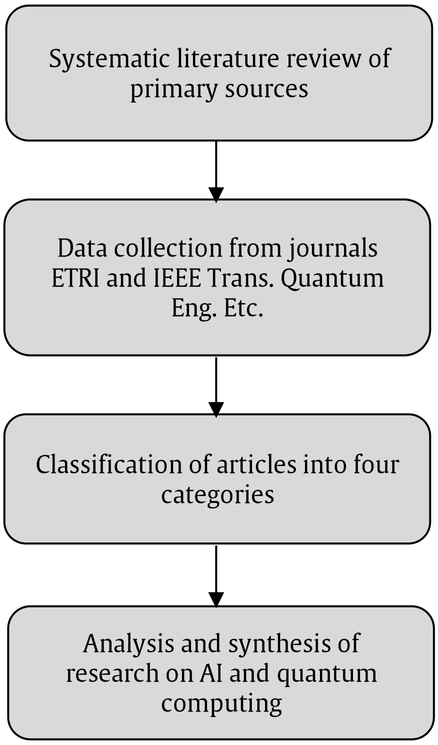

Figure 1. Stages of the research systematic process

RESULT

Before presenting a table summarizing the main findings of the various studies, it is important to provide a general analysis of the direction and focus of the research conducted in the special issue of the ETRI journal entitled Next-Gen AI and Quantum Technology. These scientific studies illustrate the growing synergies between artificial intelligence (AI) and quantum computing technologies, especially in driving future digital systems' efficiency, security, and adaptive capabilities.

Based on the results of the literature review of the thirteen articles, it can be concluded that the primary focus of research is divided into four strategic areas: (1) development of Quantum-AI (QAI) algorithms and architectures, (2) optimization of computing systems and power efficiency, (3) quantum communication technology and information security, and (4) quantum-AI-based intelligent surveillance systems. Each category contains different approaches in theory, techniques, and applications, but has one common thread: the drive towards faster, smarter, safer, and more power-efficient computing systems.

This analysis formed the basis for the following table, which summarizes the research focus, methods or approaches used, and key results of each article. This table not only helps the reader understand the diversity of innovations presented but also shows how each study makes a specific contribution to the development of current and future quantum-AI technologies.

Table 1. Summary of Recent Studies on Quantum-AI Integration

No.	Title	Research Focus	Method / Approach	Results / Key Findings
1.	Trends in Quantum Reinforcement Learning: State-of-the-Art and the Road Ahead (Park and Kim, 2024)	Recent developments and trends in Quantum Reinforcement Learning (QRL)	Quantum Neural Networks (QNN), Multi-Agent Systems, Hybrid Quantum-Classical Learning	Improved learning efficiency in AI through quantum entanglement and superposition, great potential in Federated Learning and Autonomous Control.
2.	Optimal Execution of Logical Hadamard with Low-Space Overhead in Rotated Surface Code (Lee et al., 2024)	Optimization of Hadamard operations in quantum codes to improve the stability of quantum systems	Boundary Deformation, Logical Flip-and-Shift	Reduced space overhead up to 4 times more efficient than previous methods, supporting quantum computing stability.
3.	Quantum Electrodynamical Formulation of Photochemical Acid Generation (Lee, 2024)	Application of Quantum Electrodynamics (QED) in photolithography to improve semiconductor manufacturing precision	Quantum mechanical simulation of photochemical acid formation	Improves deprotection probability and photoresist durability, important for extreme ultraviolet (EUV) lithography.
4.	Fabrication of Low-Loss Symmetrical Rib Waveguides for Quantum Photonics (Kim et al., 2024)	Development of quantum-based optical waves for quantum communication and computing	Etching optimization on LNOI rib waveguide	Reduction of light propagation loss to 0.16 dB/cm, enabling the development of more stable quantum photonic chips.
5.	Metaheuristic Optimization Scheme for Quantum Kernel Classifiers (Tjandra and Sugiarto, 2024)	Optimization of quantum kernel-based data classification for machine learning	Genetic algorithm, directed graph entanglement	Improving dataset classification accuracy with genetic evolution-based optimization is more efficient than classical methods.
6.	Free-Space Quantum Key Distribution Transmitter System (Kim, Lim, et al., 2024)	Quantum communication security with Quantum Key Distribution (QKD)	BB84 Protocol, Wavelength-Division Multiplexing (WDM)	Multiplexing efficiency is significantly improved, with an error rate as low as 0.62%, enhancing the security of quantum encryption.
7.	PF-GEMV: Utilization Maximizing Architecture for GPT-2 Inference (Kim, Lee, et al., 2024)	AI GPT-2 model processing optimization for power efficiency and speed	Port-Folding GEMV Scheme	Increased processing utilization to 93.7%, AI throughput increased 7.5x faster than conventional systems.
8.	SNN eXpress: Low-Power AI-SoC Development (Jang et al., 2024)	Development of power-efficient AI-based Spiking Neural Networks (SNN)	Ultra-Wide Area Spiking Neural Networks (UWA-SNNs), design automation	Significantly improved power efficiency, supporting the use of AI in mobile and IoT devices.
9.	XEM: Tensor Accelerator for AI Supercomputing (Jeon et al., 2024)	Optimization of tensor processing in AI Supercomputing	Parallel Floating-Point Units	Improved efficiency in linear algebra computation, supporting large-scale

No.	Title	Research Focus	Method / Approach	Results / Key Findings
				deep learning applications.
10.	NEST-C: Deep Learning Compiler Framework (Park et al., 2024)	Optimization of deep learning model compilation	Profiling-based Quantization, Dynamic Graph Partitioning	Reduce AI processing latency and increase throughput in deep learning inference.
11.	Mixed-Mode SNN Crossbar Array (Oh et al., 2024)	Spiking Neural Networks (SNN) hardware architecture for next-generation AI	Embedded Dummy Switch, Pre-Charge Scheme	Reducing errors in SNN-based computation, supporting power efficiency in AI systems.
12.	Asynchronous Interface Circuit for Multi-Core SNNs (Kim, Oh, et al., 2024)	Multi-core interface design for Spiking Neural Networks (SNN)	Nonlinear Connectivity, Multi-Pipeline Processing	Processing throughput increased by up to 53%, improving parallel processing efficiency in multi-core systems.
13.	AONet: Attention Network for Unsupervised Video Anomaly Detection (Rakhmonov et al., 2024)	Anomaly detection in unsupervised video	Attention-based Neural Network, OptAF Algorithm	The AUC reached 97% on the UCSD Ped2 dataset, effectively detecting suspicious activity in CCTV video footage.

The special issue of Next-Gen AI and Quantum Technology shows that integrating artificial intelligence (AI) with quantum computing has rapidly developed in various aspects, including machine learning optimization, data security enhancement, big data processing, and energy efficiency. Based on the results of the review of the contents of Table 1, it can be concluded that most studies adopt experimental and simulation approaches in the development of artificial intelligence (AI) systems integrated with quantum technology. The methods used can be classified into four main categories: simulation and hardware design, optimization of learning algorithms and models, implementation of quantum communication systems, and evaluation of real-time applications. Studies belonging to the first category, such as the development of PF-GEMV, XEM, and SNN eXpress, focus on hardware architecture design for inference efficiency and energy saving. The second category, such as the research on quantum kernel classifiers and quantum reinforcement learning, emphasizes improving classification performance and training efficiency by utilizing the superposition principle and quantum entanglement.

Meanwhile, the implementation of secure communication based on Quantum Key Distribution (QKD) offers a practical solution with a low error rate without the complexity of optical alignment. On the application side, research such as AONet demonstrates the utilization of deep learning-based AI in real-time video anomaly detection, with high accuracy on benchmark datasets. Quantum Key Distribution (QKD) has successfully improved data protection with low error rates in cybersecurity, making quantum cryptography the new standard in financial systems, telecommunications, and government infrastructure. Meanwhile, research in quantum-based AI hardware architectures, such as Mixed-Mode SNN Crossbar and Asynchronous Multi-Core SNN, successfully reduced error rates and increased processing throughput, enabling the development of more stable and power-efficient AI. On the other hand, research on GPT-2 Optimization and Tensor Accelerator for AI Supercomputing showed that improving the efficiency of AI infrastructure can reduce processing latency and increase inference throughput of deep learning models. At the same time, AONet proved effective in detecting video anomalies in real-time for intelligent surveillance systems. Most studies in this document are quantitative, applicable, and oriented towards solving real problems, such as energy efficiency, classification accuracy, system throughput, and digital communication security. The overall findings reflect the direction of quantum-AI research, which is increasingly focused on technology integration on an industrial scale and big data-driven digital societies.

DISCUSSION

The review of the thirteen scientific articles in this special issue of the ETRI Journal illustrates the dynamic research landscape in integrating quantum computing and artificial intelligence (AI) technologies. By emphasizing aspects of performance, energy efficiency, hardware architecture, security, and intelligent detection capabilities, all articles present important contributions that can serve as a strong basis for further scientific publication development. Based on the analysis, the key results can be grouped into four main focuses that form a framework for developing academic publications.

Quantum-AI Algorithm and Architecture Development

The development of Quantum-AI (QAI) algorithms and architectures is one of the main focuses in cross-disciplinary research that combines artificial intelligence (AI) and quantum computing. QAI algorithms are designed to optimize the machine learning process by utilizing fundamental quantum principles such as superposition and entanglement, which theoretically enable parallel processing of information on a scale far beyond the capabilities of classical computers (Kommadi, 2020). One important focus of this development is the construction of quantum neural network architectures and quantum-based optimization models that can be used in various cloud computing applications.

Papers by Park and Kim (2024) specifically outline the development of Quantum Reinforcement Learning (QRL) theory and its integration with Quantum Neural Networks (QNN). This model shows advantages in fast training and high scalability, and opens up opportunities for implementation in federated learning and autonomous control. Adding value to this development, Tjandra and Sugiarto (2024) proposed a genetic algorithm-based optimization approach to design quantum kernel classifiers via entanglement-directed graphs. The study showed that efficient quantum circuit design can significantly improve classification accuracy and F1 score on various datasets.

In theoretical and engineering contexts, quantum-inspired neural networks have been discussed as an efficient approach to representing quantum data and in-ground state optimization of complex physical systems. This approach provides faster solutions than conventional model training methods (Chen and Luo, 2024). Accordingly, hybrid platforms such as TensorFlow Quantum are important for combining the power of classical and quantum processing, as they can overcome the limitations of quantum hardware and improve the performance of algorithms such as Quantum Support Vector Machine (QSVM) and QNN in classification and big data decision making (Kumar et al., 2024).

In terms of algorithm implementation, Quantum Variational Algorithms have proven to be effective for solving complex data optimization and classification tasks, with exponential advantages in processing that cannot be achieved by classical AI (Hadap and Patil, 2024). Optimization of quantum circuits and compilation processes, including quantum circuit synthesis and AI-based qubit mapping, is also an important focus in improving the efficiency of implementing quantum algorithms in real hardware.

Concrete application examples are seen in using QSVM and QNN for image classification, pattern recognition, and natural language processing tasks. These technologies, which rely on quantum principles such as quantum annealing and entanglement, are proven to deliver faster and more energy-efficient performance than classical methods, and have been applied in the medical, financial and energy sectors where large-scale data processing efficiency is demanded (Lohia, 2024).

Optimization of AI Computing System and Infrastructure

Optimization of computing systems and artificial intelligence (AI) infrastructure is a major challenge in the big data era, where the need for large-scale data processing and the complexity of AI models continues to increase. Quantum computing is a potential solution to accelerate the calculation process, especially in solving optimization and classification problems that are difficult to solve by classical approaches. By implementing algorithms such as Quantum Support Vector

Machine (QSVM), Quantum Neural Networks (QNN), and Quantum Variational Algorithms, these technologies enable faster AI model training, simultaneous big data processing, and more efficient machine learning based decision making (Lohia, 2024).

Attempts to improve the inference efficiency of large models such as GPT-2 are reflected in cutting-edge architectural and software innovations. PF-GEMV, a matrix-vector multiplication (GEMV) processing architecture developed with the port-folding technique, successfully increased utilization by 93.7% and improved throughput by 7.5 times, making it highly effective for large-scale deep learning model inference (Kim, Lee, et al., 2024). Meanwhile, NEST-C is a heterogeneous deep learning compiler framework that reduces latency and improves inference performance on various AI accelerators by integrating optimization strategies such as quantization and graph partitioning (Park et al., 2024). Rather, XEM is a tensor accelerator based on an outer-product architecture designed to support hyperscale AI processing in supercomputing environments such as AB21 (Jeon et al., 2024). These three innovations demonstrate that efficiency improvements in the execution of AI models depend not only on the algorithm but also on optimizing the underlying hardware and compilation infrastructure.

In addition to local computing efficiency, the integration of quantum computing with cloud architecture and distributed systems has led to new approaches in security and processing flexibility. The MPC-QNC framework, which combines Physical Quantum Key Distribution (PQKD), post-quantum cryptography, and federated learning, is developed as a distributed quantum system that is both resilient to external attacks and efficient in inter-node collaboration in large networks (Yavuz et al., 2022). Along with this approach, the importance of integration between high-performance computing (HPC), cloud computing, and quantum computing to form a hybrid architecture that brings together the strengths of classical AI and quantum AI synergistically is also emphasized in the literature (Gropp et al., 2020). The approach aims to remove silo constraints in the development of future AI infrastructure. It is also supported by a multi-agent reinforcement learning model, which formulates intelligent resource allocation in quantum networks as a stochastic programming problem to improve energy efficiency, qubit fidelity, and scalability in large-scale generative AI tasks (Xu et al., 2024).

The tangible contribution of this technology is also evident in the financial sector. Atadoga et al. (2024) emphasize that quantum computing can be used to solve market prediction problems, risk modeling, and encryption of sensitive data, all of which require large-scale nonlinear optimization. They state that integrating AI and quantum computing could be the foundation for building a future financial infrastructure that is fast, accurate, and secure. However, the integrative challenges are still considerable. The limited number of qubits, the insufficient system stability, and the high cost and technical complexity of quantum infrastructure are major obstacles to the widespread adoption of this technology. Therefore, as explained by Ahmadi (2023), collaboration between technology and ethics is needed in designing regulatory and policy frameworks that can ensure the safety, sustainability, and inclusiveness of AI-quantum in the future.

Power-Efficient and SNN-based Hardware Design

Power-efficient hardware design based on Spiking Neural Networks (SNN) is a strategic solution in the development of efficient and sustainable artificial intelligence (AI) systems, especially for edge computing applications and Internet of Things (IoT)-based devices. Unlike conventional neural networks based on the frequency of neuron activity, SNNs mimic the working mechanism of the biological brain with an event-driven approach that only activates neurons when a stimulus is received. This enables high energy efficiency while maintaining competitive pattern recognition capabilities. This approach has proven effective in various experiments focused on reducing power consumption without compromising model accuracy.

One efficient approach is that of Yang and Song, who developed a non-leaky neuron prediction method and managed to reduce power consumption by 19.75%, with a decrease in accuracy of only 0.85%. This shows that energy efficiency can be achieved without significant performance loss (Yang and Song, 2020). Additionally, research by Jang et al. presented SNN eXpress, an automated tool for AI-SoC design based on Unsigned Weight Accumulating SNN (UWA-

SNN). With this automation, hardware development becomes faster and scalable for power-efficient applications (Jang et al., 2024).

The innovation was the development of a 28nm CMOS chip-based crossbar mixed-mode SNN architecture, which successfully demonstrated high efficiency in visual pattern recognition and low power consumption. This prototype shows that combining dummy-switch and pre-charge node techniques can minimize errors due to parasitic capacity in neuromorphic systems (Park et al., 2024). Multicore asynchronous interface developed to support nonlinear connectivity, with the ability to efficiently send spikes at only 1.7 picojoules per event, making it suitable for real-time AI edge devices that require fast and continuous processing (Oh et al., 2024).

Hardware implementation of the SNN was also developed through FPGAs. The Xilinx FPGA-based SNN was designed to support over 16,000 neurons and 16.8 million synapses with a power consumption of only 0.477 W, and achieved 97.06% accuracy on MNIST classification, demonstrating that FPGAs can be a flexible and efficient solution for testing neuromorphic architectures (Han et al., 2020). A non-Von Neumann approach via network-on-chip architecture is used to design large-scale digital neuromorphic cores with very low power consumption of only a few milliwatts (Fan et al., 2019).

Not only digital approaches, but analog architectures also show remarkable efficiency. Venker et al. developed a system based on leaky integrate-and-fire neurons and synapses based on Spike Timing Dependent Plasticity (STDP) on a 65 nm CMOS chip, with energy consumption of only 2.1 pJ per spike and 20 pJ per synaptic operation. This demonstrates that analog techniques can produce similar efficiency to digital systems, with lower complexity (Venker et al., 2023). Combining Resistive RAM (RRAM) with SNN was performed for reinforcement learning tasks, including Rush Hour game simulation, and showed high energy efficiency with better adaptation capability (Kim et al., 2021).

Furthermore, spike coding techniques are becoming an important area in SNN efficiency improvement. Time-To-First-Spike (TTFS) based neurons designed with analog NOR circuits were successfully used to achieve up to 15-fold more power efficiency than conventional rate-coded approaches (Oh et al., 2020). The ternary spike encoding method was enhanced to allow the classification process in only one step while maintaining high accuracy on datasets such as MNIST and Fashion-MNIST (Sun et al., 2022). Within the context of always-on devices, an ultra-low power architecture based on clock- and power-gating techniques was developed to consume only 75 nW of power when idle and less than 300 nW when active, making it highly efficient for applications such as keyword spotting and constant event detection without sacrificing predictive performance (Chundi et al., 2021).

Table 2. Summary of SNN-based power-saving hardware inventions

No	Key Technologies	Power Consumption	Application/Output
1.	Non-leaky prediction	19,75% power	Stable accuracy, efficient
2.	SNN eXpress – Tool otomatis UWA-SNN	Save energy	AI-SoC fast design
3.	Mixed-mode crossbar CMOS 28nm	411 μW	Pattern recognition efficiency
4.	Multi-core asynchronous interface	1,7 pJ / spike	Real-time edge AI
5.	SNN di FPGA Xilinx	0,477 W	97.06% accuracy (MNIST)
6.	Network-on-Chip neuromorphic	~miliwatt	Digital image recognition
7.	CMOS 65nm STDP	2,1 pJ / spike	High synaptic efficiency
8.	RRAM SNN to RL	High efficiency	Game-based learning
9.	TTFS Neuron NOR	15× more efficient	Power-saving coding
10.	Ternary spike encoding	1-step simulation	MNIST high accuracy
11.	Clock- & power-gated always-on SNN	<300 nW active	Keyword spotting with minimal consumption

Security and Quantum Communications and Surveillance Applications

Quantum communication and AI-quantum-based surveillance technologies have made significant progress, especially in addressing the data security challenges and efficiency of intelligent detection systems. Quantum communication offers unparalleled theoretical security through Quantum Key Distribution (QKD), which utilizes the entanglement and superposition principles in quantum mechanics to securely distribute cryptographic keys. One application is to introduce a BB84 protocol-based QKD transmitter system with integrated Wavelength Division Multiplexing (WDM) filters. The system achieves a key rate of 1.6 Mbps and an error rate of only 0.62% without needing a complex optical alignment process. It is a practical and efficient approach for quantum communication in real-time systems and secure networking applications (Kim et al., 2024).

These advantages align with previous studies, which mention that QKD protocols, both with discrete and continuous encoding, have been successfully implemented in photonic communication systems and enable secure key distribution even in large-scale network scenarios (Diamanti, 2021). Practically speaking, the system not only enhances the security of sensitive data but also has the potential to be applied in national infrastructures that require encryption impenetrable by classical algorithms, including in the government, banking, and military sectors (Aware and Pande, 2023). Meanwhile, AONet is an attention network architecture for unsupervised video anomaly detection in intelligent surveillance systems. It combines an innovative activation function, Optional Activation Function (OptAF), with a residual autoencoder architecture, enabling efficient recognition of spatial and temporal anomalies. Evaluation on the UCSD Ped2 dataset shows that AONet achieves high accuracy with an Area Under the Curve (AUC) of 97.0%, making it one of the leading models in video-based anomaly detection (Rakhmonov et al., 2024).

This reflects a new trend in fifth-generation surveillance systems or Surveillance 5.0, emphasizing the system's ability to detect threats in real-time, perform automated responses, and adjust surveillance strategies based on environmental dynamics (Vivekanandam, 2024). Correspondingly, the incorporation of AI and quantum technology in models such as Quantum-RetinaNet has shown significant improvements in object detection in densely populated areas, overcoming conventional models' accuracy and speed limitations (Shah et al., 2023). The strengthening of video-based surveillance systems also involves quantum authentication. A quantum key-based authentication system that integrates efficient key matching and provides resilience against quantum computing-based attacks. With key matching efficiency reaching 70.16%, the system can be applied to large-scale surveillance networks such as smart cities and intelligent traffic systems (Li et al., 2023).

However, these technological advances also invite ethical and policy debates. The use of quantum communications by countries such as China and Europe to build surveillance systems immune to eavesdropping raises profound questions about the limits of privacy and the potential for abuse of power in mass surveillance systems (Lin and Wolff, 2019). From a more critical perspective, quantum technology can change the paradigm of identity measurement, from fixed to dynamic and contextual, thus opening up space for resistance to the hegemony of an increasingly invisible but highly controlling global surveillance system (Brandimarte, 2022). Thus, advances in quantum communication and AI-quantum-based surveillance not only offer technical solutions in security and efficiency but also require thorough regulation, transparency, and ethical evaluation so that their application truly benefits society and does not create new power imbalances in the digital era.

Table 3. AI-Quantum-based Communication and Surveillance Discovery

No.	Researcher	Technology / Model	Key Contributions	Outcome/Performance
1	(Kim et al., 2024)	QKD transmitter with WDM filter	Eliminates the need for complex optical alignment in quantum communication.	Key rate 1,6 Mbps, error rate 0,62%
2	(Rakhmonov et al., 2024)	AONet (Attention Network + OptAF)	Spatio-temporal-based unsupervised video anomaly detection.	AUC 97,0% at UCSD Ped2
3	(Li et al., 2023)	Quantum key-based video authentication	Improved matching efficiency and protection from quantum attacks.	Matching rate of 70.16%, resistant to Q-computing attacks
4	(Shah et al., 2023)	Quantum-RetinaNet (QCNN + RetinaNet)	Real-time object detection in high density.	Higher accuracy and speed than classic models
5	(Vivekanandam, 2024)	Quantum AI Optimization for Surveillance 5.0	AI-quantum integration in adaptive and responsive security systems	Real-time threat detection with dynamic adaptation

CONCLUSION

This research presents a systematic synthesis of cutting-edge studies that address the application of quantum computing-based artificial intelligence technologies in various applied contexts, ranging from anomaly detection and secure communication systems to energy-efficient hardware design. Based on an analysis of 13 publications in the ETRI Journal 2024 special issue, it can be concluded that integrating quantum mechanical principles into machine learning systems and AI infrastructures has led to new methods and architectures that are much more efficient than classical approaches. For example, the development of Quantum Reinforcement Learning and Quantum Kernel Classifiers showed significant advantages in training efficiency, classification accuracy, and scalability. These findings indicate that the utilization of quantum phenomena such as entanglement and superposition is not only theoretical but has also been experimentally tested in several real-world applications.

On the hardware and energy efficiency side, Spiking Neural Networks (SNN) technology is proving to be a promising solution for developing power-efficient AI systems suitable for edge and IoT devices. Researches such as developing SNN eXpress, mixed-mode SNN crossbar, and multi-core asynchronous interfaces show great potential in reducing power consumption without sacrificing performance. Furthermore, computational efficiency in tensor processing for large AI models is also improved thanks to architectures such as PF-GEMV and XEM, which are specifically aimed at accelerating inference and optimizing the performance of modern AI processors. Meanwhile, in terms of security, developing a WDM filter-based Quantum Key Distribution (QKD) system was capable of high key and low error rates, indicating that quantum-based secure communication is getting closer to practical implementation.

In the field of smart surveillance, unsupervised approaches such as the one undertaken in the development of AONet show remarkable effectiveness in real-time video anomaly detection, which is highly relevant for public safety and smart surveillance applications. The advantages of this approach are not only in performance metrics such as high AUC, but also in the efficiency and flexibility of the architecture that enables integration in real operational systems. However, challenges remain, such as noise in quantum hardware, qubit limitations, and the need for algorithms more tolerant of non-ideal experimental conditions.

Based on these results, it is recommended that future research and development be directed more towards the maturation of quantum hardware infrastructure and the optimization of quantum-based AI models that are resistant to environmental disturbances. In terms of applications, sectors such as health, finance, defence, and transportation are the most promising priorities to be accelerated with this technology. In addition, comprehensive regulatory policies and ethical frameworks are needed, especially in developing quantum-based surveillance and communication systems, so that technology does not pose new risks to people's privacy and security rights. Multidisciplinary, collaborative, and application-oriented research will be key in realizing an inclusive, efficient, and reliable AI-quantum ecosystem.

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