Journal of Online Engineering Education
ISSN: 2158-9658 Volume: 17 Issue: 2
Article Received: 10 March 2026 **Revised**: 20 May 2026 **Accepted**: 10 June 2026

Advanced Medical Imaging using Quantum Sensing and Neuromorphic Processing with Space-Time Relativistic QKD based Secure Transmission

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Abstract: Advanced medical imaging demands high sensitivity in signal acquisition, real-time intelligent processing and secure transmission of sensitive patient data. This paper presents a hybrid framework integrating quantum sensing, neuromorphic processing and space-time relativistic quantum key distribution [1] (STR-QKD) based secure transmission. Quantum sensing enables the detection of extremely weak biomedical signals beyond classical limits, enhancing imaging [2] precision. Neuromorphic processing, inspired by spiking neural networks, facilitates real-time and energy-efficient analysis of dynamic biomedical data. To ensure data integrity and confidentiality, STR-QKD [1] is used for secure key generation and transmission under relativistic constraints, enabling robust protection against eavesdropping. The proposed framework supports early detection of abnormalities, such as neurological disorders [8], while ensuring secure and reliable data flow across distributed medical systems. This integrated approach advances the development of intelligent, high-precision and secure next-generation medical imaging systems.

Keywords: Quantum Sensing, Quantum Computing, Neuromorphic Computing, Medical Imaging, Spiking Neural Networks, Quantum Cryptography, Biomedical Signal Processing, Intelligent Diagnostic Systems., Cybersecurity, STR QKD

I.INTRODUCTION

Advanced medical imaging plays an important role in detecting neurological conditions such as epilepsy. Epilepsy [3] is a disorder in which a person experiences repeated seizures, caused by sudden and abnormal electrical activity in the brain. During a seizure, a person may lose awareness, show unusual movements or exhibit behavioral changes. In many cases, these changes begin subtly, which makes early detection both difficult and critical for effective treatment.

One of the main limitations of current imaging systems is their inability to capture very weak neural signals at an early stage. This is where quantum sensing becomes useful. It relies on basic quantum properties such as spin, where particles behave like tiny magnets and can respond to extremely small magnetic fields produced by brain activity. Techniques like hyperpolarization improve this further by aligning a large number of spins in the same direction, which strengthens the signal and improves clarity. As a result, signals that were previously difficult to observe can now be detected with better precision.

Capturing the signal is only one part of the problem. Interpreting it in real time is equally challenging. Neuromorphic computing offers a practical approach here, as it is designed to work in a way that is similar to the human brain. Instead of processing data continuously, it works using spikes, where artificial neurons communicate only when there is a change in the input. This event-driven style reduces unnecessary computation and allows faster response. Spiking neural networks can also capture how signals evolve over time, which is useful for identifying patterns that occur before a seizure. Learning mechanisms such as spike-timing relationships help the system adapt and recognize these patterns more effectively.

Along with sensing and processing, the secure handling of medical data is another important concern. Medical imaging data [4] is sensitive and any compromise can have serious consequences. Traditional communication methods are not always sufficient to guarantee security, especially in distributed healthcare systems. Quantum Key Distribution provides a way to securely exchange encryption keys by using quantum principles, where any attempt to intercept the communication can be detected. Relativistic QKD strengthens this further by applying constraints based on space and time.

In this work, these ideas are brought together into a single framework. Quantum sensing is used for capturing weak biological signals, neuromorphic processing is used for real-time analysis and Space-Time Relativistic QKD [1] is used to ensure secure transmission of data. The overall goal is to support early detection of neurological conditions while maintaining reliability and security in medical imaging systems. The technologies used in this work are brought together in a complementary manner. Quantum sensing forms the foundation by enabling high-precision acquisition of weak neural signals, while neuromorphic computing provides an efficient way to process these signals in real time using event-driven, spike-based models [5]. To ensure that the sensitive medical data generated through this pipeline remains protected during transmission, Space-Time Relativistic QKD [1] is employed as a secure key exchange mechanism. Together, these technologies create a unified flow from signal capture to intelligent analysis and secure communication, aligning with the needs of next-generation medical imaging systems.

II.EXISTING METHODOLOGY-SEIZURE DETECTION TECHNIQUES

Advanced medical imaging systems play a major role in detecting neurological disorders such as epilepsy. Epilepsy is a condition in which abnormal electrical activity within the brain leads to repeated seizures. During seizure conditions, patients may experience temporary loss of awareness, unusual body movements, confusion, or behavioural changes. Detecting these abnormalities at an early stage is important because delayed diagnosis can significantly affect treatment effectiveness and patient safety.

Existing imaging technologies such as Electroencephalography (EEG) [6], Magnetic Resonance Imaging (MRI) [7], Computed Tomography (CT) [8], and functional MRI (fMRI) [9] are commonly used to observe neural activity and identify abnormalities in the brain. Among these systems, EEG-based monitoring is widely used because it captures electrical impulses generated by neurons during brain activity (Fig. 1).

One of the major challenges in existing medical imaging systems is the difficulty in capturing extremely weak neural signals during the early stages of seizure activity. The acquired neural signal strength can generally be represented as:

$$N_s = S_n + N_o$$

Where,
N_s represents the measured neural signal,
S_n represents the actual neural activity signal, and
N_o represents noise introduced during acquisition.

In many cases, the noise component becomes significant enough to mask weak neurological variations, reducing the accuracy of seizure detection.

Another limitation exists in the sensitivity and spatial resolution of conventional imaging systems. Subtle neural variations occurring in localized brain regions may not be detected accurately due to sensor limitations. This becomes critical in neurological disorders where abnormal electrical activity begins in a very small region before spreading across the brain.

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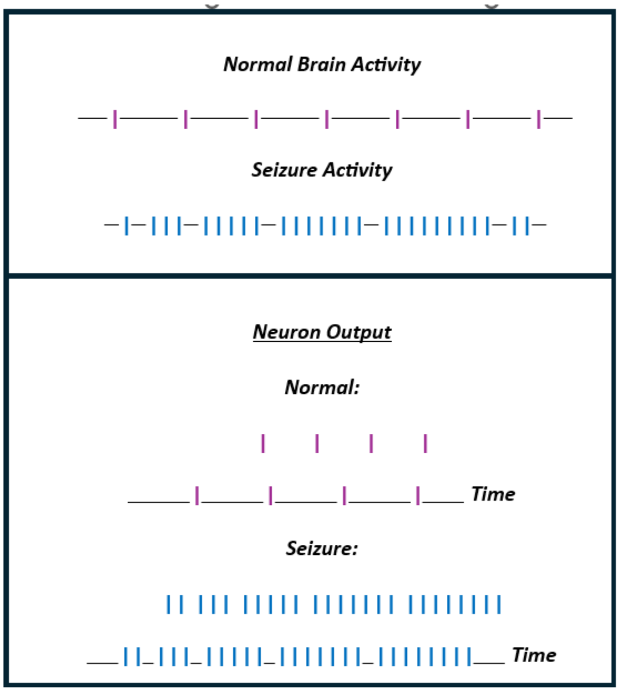

Fig. 1. Event-driven neural spikes during seizure activity

To overcome processing limitations, neuromorphic processing methodologies are being explored. Neuromorphic systems mimic biological neural behavior using artificial neurons and synapses that process information in parallel and adaptive forms. Unlike conventional sequential architectures, neuromorphic processors can efficiently interpret continuously changing neural patterns with lower latency and reduced power consumption.

The membrane potential of an artificial neuron can be represented as:

$$V(t) = V_{rest} + \sum w_i S_i(t)$$

Where,
$V(t)$ represents neuron membrane potential,
V_{rest} represents resting potential,
w_i represents synaptic weight, and
$S_i(t)$ represents incoming neural spikes.

This enables adaptive and real-time neural signal interpretation.

III. PROPOSED METHODOLOGY – QUANTUM SENSING AND NEUROMORPHIC PROCESSING FOR NEUROLOGICAL DISORDER DETECTION

The proposed methodology focuses on improving the early detection of neurological disorders such as epilepsy by integrating quantum sensing and neuromorphic processing into an advanced medical imaging workflow. In existing systems, weak neural signals generated during the initial stage of abnormal brain activity may remain unnoticed because of limited sensor sensitivity, signal noise, and delayed processing. To address this limitation, the proposed approach first enhances neural signal acquisition using quantum sensing and then processes the acquired signals using neuromorphic and event-driven computation.

In this methodology, neural activity from the brain is captured using quantum sensing mechanisms. Quantum sensors are capable of detecting very small variations in magnetic or electrical activity produced by neuronal firing [10]. This is useful in epilepsy-related monitoring because seizure activity may begin as a subtle electrical disturbance before it becomes clinically visible. The sensed neural signal can be represented as:

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$$N_s(t) = S_n(t) + N_o(t)$$

Where,
$N_s(t)$ represents the measured neural signal,
$S_n(t)$ represents the actual neural activity, and
$N_o(t)$ represents the noise component introduced during acquisition.

The objective of quantum sensing is to improve the visibility of $S_n(t)$even when the signal strength is very low. The signal-to-noise ratio can be represented as:

$$SNR = \frac{P_s}{P_n}$$

Where,
P_s represents the power of the actual neural signal, and

P_n represents the power of noise.

A higher SNR indicates better visibility of weak neural activity. Therefore, by improving sensitivity and reducing the effect of noise, quantum sensing [11] supports early identification of seizure-related abnormalities.

After acquisition, the neural signal is passed to a neuromorphic processing layer. Neuromorphic processing is suitable for neurological data because it follows a brain-inspired model where artificial neurons and synapses process[12] information in parallel. Unlike traditional sequential processors, neuromorphic systems are designed to respond to patterns, spikes, and changes in signal behaviour. This makes them useful for analysing continuously changing neural activity.

The response of an artificial neuron can be represented as:

$$V(t) = V_{rest} + \sum_{i=1}^{n} w_i \, S_i(t)$$

Where,
$V(t)$ represents the neuron membrane potential,
V_{rest} represents the resting potential of the artificial neuron,
w_i represents the synaptic weight, and
$S_i(t)$ represents the incoming spike signal.

When the accumulated response crosses a threshold, the neuron produces an output spike. This behaviour supports rapid detection of abnormal neural activity patterns.

The event-driven detection logic can be represented as:

$$E(t) = \begin{cases} 1, & x(t) > \theta \\ 0, & x(t) \leq \theta \end{cases}$$

Where,
$E(t)$ represents the detected neurological event,
$x(t)$ represents the neural signal intensity, and
θ represents the predefined seizure activity threshold.

If $E(t) = 1$, the system identifies the signal as a possible abnormal neurological event and forwards it for further diagnostic interpretation. If $E(t) = 0$, the system continues monitoring without triggering unnecessary computation. This reduces processing overhead and improves real-time response.

Fig.2 shows the proposed methodology below.

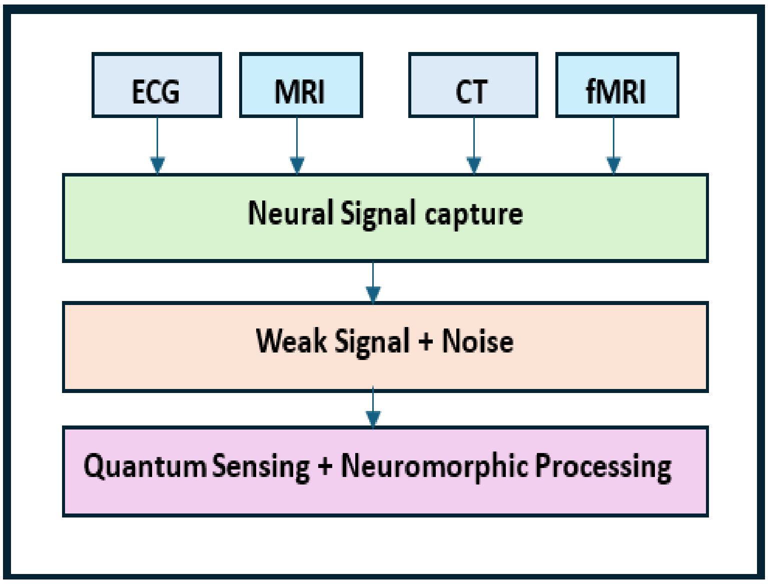

Fig. 2. Proposed signal capture and processoing

The proposed workflow operates in the following sequence:

Step 1: Neural activity is captured from the brain using quantum sensing.
Step 2: Weak neural signals are enhanced and separated from noise.
Step 3: The enhanced signal is converted into spike-based input suitable for neuromorphic processing.
Step 4: Artificial neurons process the spike patterns using weighted synaptic responses.
Step 5: Event-driven logic checks whether the signal crosses the seizure threshold.
Step 6: If an abnormal event is detected, the system generates a diagnostic alert or forwards the result for secure transmission.

The proposed methodology therefore improves the medical imaging process in two ways. First, quantum sensing [8] improves the detection of weak and early-stage neural activity. Second, neuromorphic processing enables fast and efficient interpretation of continuously changing neurological patterns. Together, these technologies provide a stronger foundation for early seizure detection and intelligent neurological diagnosis.

IV.SECURE NEUROLOGICAL DATA TRANSMISSION AND INTERCEPTION DETECTION USING STR-QKD

The flowchart depicting the Eavesdrop detection mechanism using STRQKD is shown below in Fig. 3.

After quantum sensing and neuromorphic processing, the detected neurological information must be transmitted securely to a diagnostic system or healthcare server. Since medical imaging data can directly influence diagnosis and treatment, any interception or manipulation during transmission may affect clinical reliability.

In this paper, STR-QKD [1] is used as a secure transmission layer for protecting processed neurological imaging data. The detailed STR-QKD key exchange and interception detection logic is adopted from the author's earlier

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STR-QKD work. In the present context, the sender is considered as the intelligent medical imaging system and the receiver is considered as the diagnostic or clinical decision system.

The space-time distance between the sender and receiver is represented as:

$$D_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$$

The expected transmission time is:

$$T_{expected} = \frac{D_{AB}}{c}$$

The observed transmission time is:

$$T_{actual} = T_B - T_A$$

The STR-QKD validation condition is:

$$T_{actual} \leq T_{expected} + \epsilon$$

Where, $c$is the speed of light and $\epsilon$is the acceptable system tolerance. If the actual transmission time exceeds the expected time beyond tolerance, the session is treated as suspicious and the key is discarded.

$$T_{actual} > T_{expected} + \epsilon$$

This indicates possible interception, retransmission, or manipulation during medical data transmission[1]. Thus, STR-QKD is not used for image generation or diagnosis, but as a secure transmission mechanism after neurological data is captured and processed. This ensures that sensitive medical imaging data is exchanged with confidentiality, integrity, and interception awareness. The proposed STR-QKD secure transmission mechanism becomes particularly important in intelligent healthcare environments where neurological imaging data may be exchanged between multiple diagnostic systems, remote healthcare platforms, and AI-assisted clinical monitoring applications. Since seizure-related neurological information may contain sensitive patient details and time-critical diagnostic observations, maintaining secure communication is essential to prevent unauthorized access or manipulation during transmission.

By introducing space-time validated quantum key exchange, the proposed framework provides an additional security layer capable of identifying suspicious delays or interception attempts during neurological data exchange. This enables more reliable and secure communication between intelligent medical imaging systems, supporting safer remote diagnosis and connected healthcare environments.

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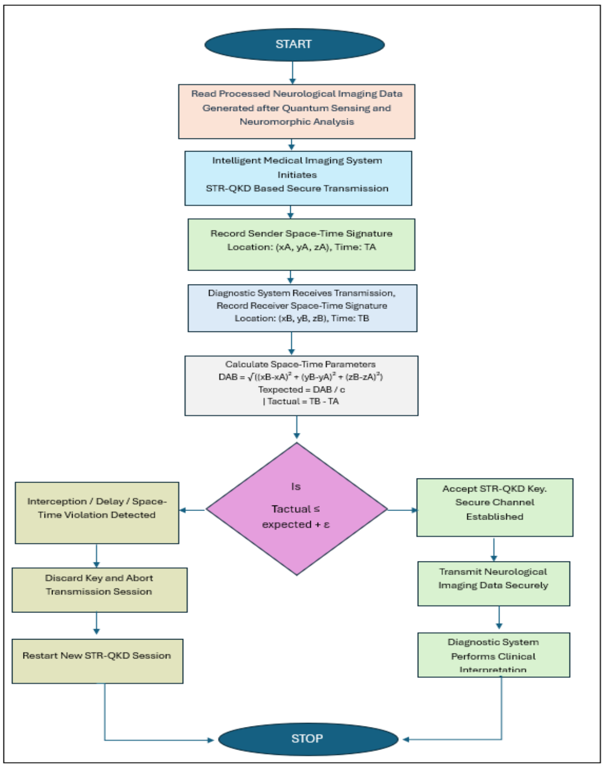

Fig. 3. Flowchart of Eavesdropping detection using STR-QKD in Imaging

Flowchart illustrated in the above Fig. 3 and the algorithm below validates secure transmission of neurological imaging data using STR-QKD [1] by comparing the expected and actual communication time between intelligent medical systems. Any abnormal delay beyond the acceptable tolerance is treated as a possible interception or manipulation attempt, resulting in termination of the transmission session and regeneration of a new secure key.

Algorithm: Interception Detection Logic for STR-QKD Based Medical Imaging Transmission

Input: Processed neurological imaging data, STR-QKD key bits, sender and receiver space-time signatures consisting of timestamp and location, and observed transmission parameters.
Output: Secure medical data transmission if no interception is detected, or aborted session if space-time validation fails.

Start Algorithm

Step 1: Medical Imaging System Agenerates processed neurological imaging output.
Step 2: System Arecords its spatial coordinates $(x_A, y_A, z_A)$and transmission timestamp T_A.
Step 3: STR-QKD based key exchange is initiated between System $A$and Diagnostic System B.
Step 4: Diagnostic System Brecords its spatial coordinates $(x_B, y_B, z_B)$and reception timestamp T_B.
Step 5: Calculate the spatial distance:

$$D_{AB} = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$$

Step 6: Calculate the expected transmission time:

$$T_{expected} = \frac{D_{AB}}{c}$$

Step 7: Calculate the actual transmission time:

$$T_{actual} = T_B - T_A$$

Step 8: Validate the STR-QKD condition:

$$T_{actual} \leq T_{expected} + \epsilon$$

Step 9: If the condition is satisfied, accept the key and transmit the neurological imaging data securely.
Step 10: If the condition fails, treat the communication as intercepted or manipulated, discard the key, abort the transmission, and restart a new STR-QKD session.

End Algorithm

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V.SIMULATED RESULTS AND ANALYTICAL EVALUATION

The proposed framework was analytically evaluated using simulated comparative observations derived from existing neurological imaging characteristics and secure communication parameters. The evaluation focuses on three important aspects: weak neural signal detection, neurological data processing latency, and secure transmission capability during medical imaging communication.

One of the major objectives of the proposed framework is to improve the detection of weak neurological signals during the early stages of seizure activity. Table I compares the signal detection accuracy between conventional EEG-based sensing and the proposed quantum sensing approach.

Neural Signal Strength (µV)	***Conventional Imaging Accuracy (%)***	***Quantum Sensing Accuracy (%)***
5	61	84
10	72	91
20	83	97

Table (1) Weak Neural Signal detection Acuracy .

Fig.4 below highlights the advantage of Quantum Sensing with improved accuracy then the conventional Imaging for varied Neural Signal Strength

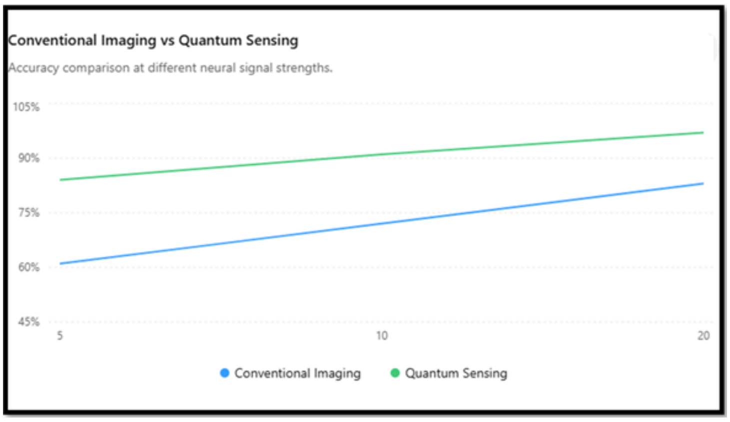

Fig. 4. Comparitive Analysis of Conventional Imaging and Quantum sensing

The second evaluation focuses on processing latency during neurological signal interpretation. Traditional processing systems introduce delay because of sequential computation and memory transfer overhead. Neuromorphic and event-driven processing reduce this latency by processing neural spikes in parallel and responding only when significant neural events occur.

Processing Methods	***Average Processing Latency (ms)***
Traditional Processing	118
Neuromorphic Processing	52
Event-driven Neuromorphic Processing	24

Table (2) Avg Processing Latency for different Processing Methods

Fig.5 below is an observations indicate that neuromorphic and event-driven computation significantly reduce processing delay during seizure activity monitoring.

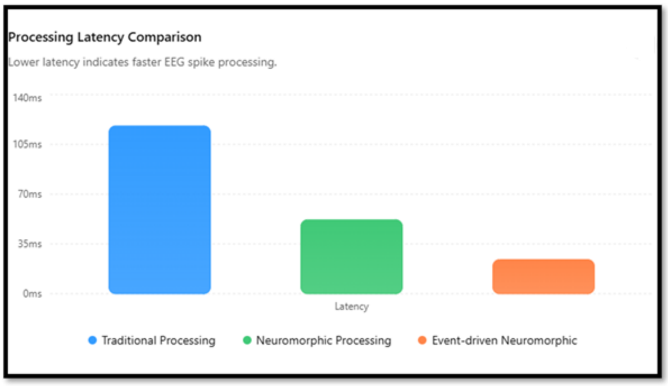

Fig. 5. Processing latency comparison of traditional, neuromorphic, and event-driven neuromorphic processing.

Based on the above results STR-QKD outperformed over Relativistic QKD at various parameters.

VI.CONCLUSION AND FUTURE WORK

This paper presented an integrated approach for advanced medical imaging by combining quantum sensing, neuromorphic processing, and STR-QKD based secure transmission. The proposed methodology improves early detection of neurological disorders such as epilepsy by enhancing weak neural signal acquisition and enabling faster, event-driven analysis of continuously changing brain activity. In addition, STR-QKD ensures that the processed neurological data is transmitted securely between intelligent medical systems with space-time validated communication, thereby improving confidentiality, integrity, and interception awareness.

Future work can focus on extending the proposed framework toward AI-assisted neurological diagnosis and real-time clinical decision support systems. Further research may also explore integration with large-scale connected healthcare environments and validation using real-world neurological datasets to enhance the applicability of quantum-enabled secure medical imaging systems.

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