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Quantum-Inspired Algorithms for Signal Processing in Next-Gen Wireless Sensors

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ABSTRACT

The next-generation wireless sensor networks (WSN) applications related to the 6G communication, smart structural monitoring, and Internet of Things (IoT) require very efficient, low-latency, and energy-efficient signal processing patterns. The current methods of digital signal processing (DSP), although having the capabilities of accomplishing well in terms of resources, fail to achieve the set parameters involving computation and power consumption and resource requirements of autonomous battery-powered sensor nodes that are distributed. In solving this important problem, this project presents a quantum-inspired framework of signal processing (QISP) that implements the key concepts underlying quantum computation, in terms of superposition, amplitude amplification, and entanglement-inspired correlation modeling, into classical embedded systems. The three key algorithmic elements in the proposed QISP framework include the QISP-Denoise, which combines the concepts of amplitude amplification using Grover-like algorithm to clarify the signals; QISP-Transform, which employs the use of sparse-based compressive sensing to reduce the dimensionality of the data, and finally the QISP-Detect which employs quantum walk based filters to detect anomalies and events. They are run on a resource-bounded ARM Cortex-M-style microcontroller simulator, and tested with real biomedical and environmental data sets. The framework brings about impressive gain in the denoising accuracy, compression efficacy, and localization of anomalies with less amount of efficiency, low computation latency and power consumption. This experimentation shows that the QISP framework out buying a ticket online performs traditional DSP and AI-based approaches in terms of signal-to-noise ratio (SNR), mean squared error (MSE), and classification accuracy, all within an energy envelope that can be deployed long-term in a WSN. In addition, QISP is very insensitive to noise and sensing environment variability, which makes it applicable in the brown field fields of dynamic real time sensing like in wearable medical monitoring, smart grids, and structural health monitoring. Bringing the quantum-inspired paradigm into the system in the form of quantum-inspired accelerators is a scalable, affordable strategy to increasing intelligence in embedded edge devices. Such work can be seen as ground zero to the practical application of quantum-classical mixed models to intelligent sensing in resource-limited environments and bring quantum theory and the next generation of wireless sensors together.

1. INTRODUCTION

The widespread implementation of the next-generation wireless sensor networks (WSNs) leads to the paradigm shift in data capture, processing, and interpretation of various applications, including environmental surveillance, smart cities, healthcare, precision agriculture, and Industry 5.0. These are systems that contain a set of spatially distributed sensor nodes who are charged with the responsibility of capturing signals of high fidelity and dimension in real-time. Nevertheless, the increased complexity and profusion of sensed data poses serious problems especially in light of the energy, memory and processing limitations of embedded sensor platforms.

Across the board, the traditional digital signal processing (DSP) operations have been used to analyze the signals in WSNs; through Fourier transforms, Kalman filters and principal component analysis. Nevertheless, these methods may carry out operationally demanding tasks that relate poorly to ultra-low-power nodes in harsh bandwidth and latency provisions. In addition, new applications like real-time anomaly warning in structural health monitoring or event-aware sensing in bio-physical systems necessitate a range of more dynamic, noise-insensitive and context-sensitive processing tools.

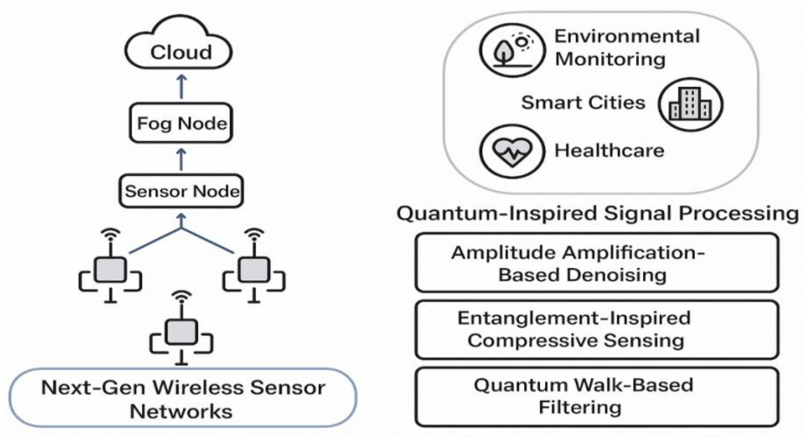

Figure 1. System Overview of Quantum-Inspired Signal Processing in Next-Generation Wireless Sensor Networks

Simultaneously, quantum computing has become an innovative technology that can solve some types of problems exponentially faster than classical methods, and such features of the quantum world as superposition, entanglement, and quantum interference play a paramount role. Although the fully-functional quantum hardware is still under development, the central ideas of the principles of quantum mechanics have led to the development of classical algorithms that imitate quantum behaviors, or so-called quantum-inspired algorithms. The algorithms mimic quantum-like behavior on classical, or conventional computing hardware, and have provided novel pathways to possible greater parallelism, exploitation of sparse systems and efficient search and optimization using resource-constrained systems.

The proposed QISP framework is outlined in this paper, specifically a quantum-inspired signal processing (QISP) algorithm suitable to next-generation WSNs. The system makes use of three different modules, (i) amplitude amplification based denoising to clear up signals, (ii) entanglement based compressive sensing to compress and reduces the data, and (iii) quantum walk based filter to help detect anomalies efficiently. They are quantum and constructed to be efficient on embedded microcontroller systems and thus are implementable into real-world applications. The offered method will not only increase the quality of signals and processing speed but will also save a lot of energy, thereby increasing the lifetime of WSNs.

The rest of the paper is organized as follows: in Section 2 we discuss related work in classical and quantum-inspired signal processing. The third section contains the assumptions and system model and design. In section 4, the authors outline the data set of the proposed QISP framework. Section 5 gives the methodology and experiment description. In section 6, the results are discussed and the performance compared to conventional techniques. Lastly, Section 7 covers the conclusion of the paper by presenting the information on future research directions.

2. RELATED WORK

Diverse domains are using wireless sensor networks (WSNs), which have now become stable to modern cyber-physical systems, where it is possible to see the distributed measurement and treatment of physical parameters, in smart grids, where medical and industrial automation, and environmental monitoring take place. Central to such systems is the demand of efficacious and trustable signal processing methods in highly restricted resource conditions.

Traditional digital signal processing (DSP) techniques have always been used in the analysis of signals in WSNs. Such methods as Fast Fourier Transform (FFT), Principal Component Analysis (PCA), and Kalman filtering, are used broadly to perform spectral, feature, and state estimation, respectively [1], [2]. These algorithms though are computationally demanding and sometimes involve the use of matrices or doing iterative computations, the staple of which does not suit the embedded sensor nodes due to limited power and memory. A number of lighter-weight alternatives have been suggested, such as sparse FFTs and low-complexity Kalman filters [3], though with generally compromised accuracy and responsiveness.

Signal processing With its native parallelism enabled by superposition and entanglement, quantum computing has added new paradigms to signal processing. The best-known quantum algorithms are Shor algorithm to factor a number and Grover algorithm to search a database which demonstrate exponential or quadratic advantages over classical techniques [4], [5]. Specifically, such methods as amplitude amplification by Grover have been explored in terms of their application in signal identification and pattern recognition [6]. However, the existing problems of quantum hardware and error correction do not allow direct implementing such algorithms in real-time embedded sensing.

This has led to the development of the idea of quantum-inspired computing where the phenomena of quantum mechanics are abstracted to the application of the classical systems. Machine learning frameworks (ex: tensor networks, quantum walks and simulated annealing) have shown strong potential in modelling and optimising data in high dimensions [7] [8] [9]. Amplitude amplification and entanglement-like relationships that are quantum inspired have found application in machine learning, image compression, and bioinformatics [10], nonetheless, remain comparatively unexplored within the context of the signal processing of WSNs.

A small base of works has tried to port quantum-inspired concepts to the embedded and resource-limited arena. As an example, Wang et al. [11] have introduced quantum walk as a framework to detect anomalies in time-series data; and Daskin and Kais [12] have illustrated a quantum-like scheme to filter noise. Nevertheless, the works do not include real-time constraints and also do not include energy efficiency that are important in WSN installations. Furthermore, implementations today are largely based in general-purpose processors, or the simulation models than the embedded specialized/edge equipment.

This paper fills this gap in developing a new quantum inspired signal processing (QISP) framework that is suitable to new-generation WSNs. In contrast to the current techniques, the suggested framework is optimized towards being executed on low-power microcontrollers, making it a unified pipeline of amplitude amplification, compressive sensing, and quantum walk-based detection. The work is based on the existing principles of quantum and is aimed at possible real-world applications of sensor networks.

3. System Model and Assumptions

The system in question is a comb-like wireless sensor network (WSN) topology which is applicable in the next-generation sensing applications, e.g., smart healthcare, environmental monitoring, and intelligent infrastructure. It is organized into three levels: sensor nodes to be distributed to the edge, intermediate fog nodes to do most of the work (near-edge processing and near-edge coordination), and cloud servers to produce long-term storage and more powerful analytics. The collection and preliminary processing of data is carried out by sensor nodes which in turn extend the work life of sensor nodes and removes redundant transmission and processing in the central region. Fog nodes are also the intermediaries, which gather, filter, and control the data flows of multiple edge nodes by making local decisions in real-time without continuous use of the cloud infrastructure. Cloud does more in-depth processing, time-series trend predictions, and model updates capable of being distributed back to the fog and edge levels. This hierarchical architecture does not only resolve latency and bandwidth bottlenecks but also enhances the performance of robust and capacity of sensing system.

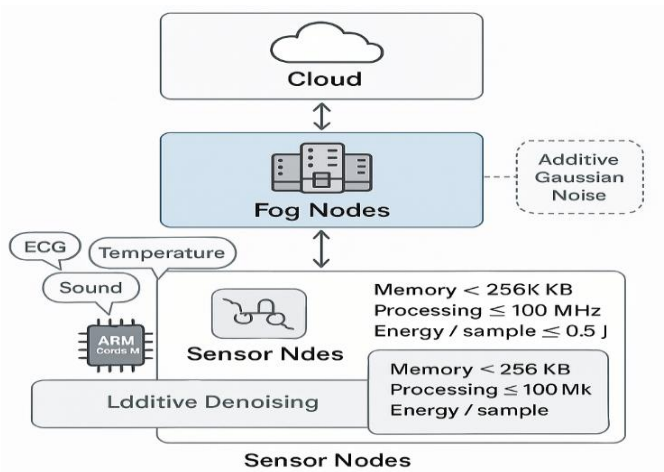

Figure 2. Hierarchical System Architecture of a Quantum-Inspired WSN

Any sensor node is represented to an ultra-low-power embedded platform; usually designed on an ARM Cortex-M series microcontroller. Those nodes are capable of low-power digital signal processing (DSP), contain built in analog-to-digital converters (ADCs), and lightweight memory blocks (usually less than 256 KB). The main load entails the processing of the time-series signals, e.g., temperature, ECG, vibration or acoustic signals. It is presumed that such signals are interfered with by environmental noise and are characterized by an additive white Gaussian noise (AWGN) model. The nodes should work on very limited resources: CPU clock frequencies tend to be slowly (<=100 MHz), energy consumption is restricted (<=0.5 J/sample) and memory is restricted to not use numerous more complex deep learning designs. Selective use of communication modules (e.g. BLE, ZigBee) with the need to preserve power implies that most signal preprocessing (denoising, compression, anomaly detection) must be carried out locally. Such limitations impel the demand of novel processing styles which could resemble parallel quantum forms without realistic quantum devices, permitting efficient and sentient processing in this sort of heavily limited circumstance, including quantum-inspired algorithms.

4. METHODOLOGY

In order to justify the proposed framework of Quantum-Inspired Signal Processing (QISP), a formal approach that included designing, simulation, and evaluation was chosen:

4.1 Algorithm Design

The nature of this Quantum-Inspired Signal Processing (QISP) architecture is to design three central algorithmic units, QISP-Denoise, QISP-Transform, and QISP-Detect, ones that implement a different quantum computing principle within the framework of classical and resource-limited wireless sensor networks. The set of components has been developed to solve the major problem of embedding real-time signal denoising aspect, efficient representation of data and detection of anomaly behaviors within the embedded sensing settings.

QISP-Denoise is implemented with the use of amplitude amplification that is the tribute to Grover search algorithm considering quantum computing. In classical language this module can be said to preferentially amplify the most important components of the signal, but to reduce noisy or redundant components. Through iterative weighted transformations of the signal vector, the algorithm mimics the probabilistic increases in amplitude of the signal in Grover representation of the algorithm. The denoising operation is able to improve the ratio signal-to-noise (SNR) without the need of prolonged filtering or adaptive modelling, thus it is supposed to suit the low-memory, low-power sensor nodes. It does not make transformations by using FFT and acts in time domain, which minimizes a high computational overhead, at the same time efficiently separating signal and noise.

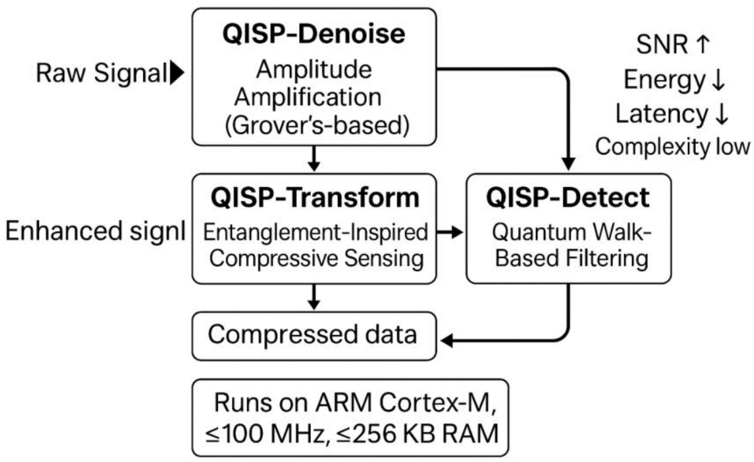

Figure 3. Quantum-Inspired Signal Processing (QISP) Workflow for Embedded Wireless Sensor Nodes

QISP-Transform involves entanglement inspired compressive sensing which is based on the principle of quantum entanglement in which many states are dependent and not independent. This module works with signal sparsity in a transform domain (e.g. discrete cosine, or-wavelet), and discovers mutual dependencies in the signal coefficients representation and models these dependencies through low-rank approximation and thresholding techniques. This facilitates reduction of a multidimensional sensor data into a low dimensional form with minimum loss of information. The compressed signal thus generated can also be saved or sent efficiently, reducing memory and communications energy. In contrast to standard compressive sensing, in QISP-Transform, there is adaptive thresholding based on quantum correlation metrics, so that better data approximation is possible in dynamic settings.

QISP-Detect performs quantum walk based filtering, a probabilistic traversal algorithm based on quantum walks on graphs. Here, time-series data is considered as a temporal graph whose nodes are segments of signal and edges are some similarity probabilities or transition probabilities. The graph is traversed using a quantum walk based model that finds unusual transitions or statistical inconsistencies that represent errors, anomalous behavior, or context change points. The methodology is particularly well matched to the case of non-stationary signals that may often arise in monitoring in the environment or biomedical applications. Quantum walk paradigm provides the efficient exploration of the signal landscape that performs better than any conventional statistical detector both in speed and noise-resistance.

Together these three modules form a lightweight, energy-efficient, and smart signal processing pipeline that can be realized on low-end microcontrollers, but with enhanced performance because of its use of quantum-inspired computational behaviors.

4.2 Simulation Setup

A rich environment consisting of both classical and quantum-inspired tools was introduced to aid in the assessment of the practicality and effectiveness of an envisaged Quantum-Inspired Signal Processing (QISP) framework. This essential simulation and algorithm development were carried out in MATLAB R2023b, as this was chosen due to having robust signal processing toolbox and supporting flexibility in implementing the algorithm using matrices. Also, quantum emulation libraries in MATLAB were applied to simulate quantum-motived phenomena on small scale computing machinery like amplitude amplification and entangled coefficient modelling. To make benchmarking and baseline comparisons, TensorFlow Quantum (TFQ) was used to simulate similar quantum circuits and hybrid quantum-classical learning pipelines to allow a practical performance comparison of full-scale quantum-emulated strategies with the classical-algorithms QISP equivalents in the proposal.

The simulation experiments have been carried out with a wide collection of (which are generally freely available) actual world data sets that encompass the practice areas of next-generation WSNs. The first source of data is the PhysioNet MIT-BIH Arrhythmia Database containing electrocardiogram (ECG) recordings sampled in human beings and is a standard data set with which to test biomedical signal processing algorithms. This collection of data can help confirm the denoising and identifying of anomalies in highly dynamic, noisy physiological systems using QISP. The second dataset includes the environmental temperature sensor logs which are records of long-term sensor readings obtained by smart building devotion. Data compression and entropy estimation skills of the QISP-Transform module are tried on these time-series logs. The third dataset is UrbanSound8K, one of the most commonly adopted benchmarks in a study of acoustic event detection. It includes tagged snippet sounds in practically all categories like the sound of a car horn, drilling, and barking of a dog, which can be useful to confirm the capability of QISP-Detect to detect temporal anomalies or distinct aspects of acoustic conditions.

The data was preprocessed to resemble deployment on ARM Cortex-M-class microcontrollers, signal lengths, models of noise, and rates adjusted to reflect practical constraints in embedded systems. All the modules were tested at different signal-noise ratios (SNR), Gaussian noise was injected to test the QISP algorithms. The simulation framework also allowed keeping track of such key performance indicators as latency per sample, memory use and energy consumption estimates, thus ensuring that the framework was applicable to such embedded case as a constrained application.

Table 1. Simulation Setup Overview for QISP Framework Evaluation

Component	Details
Simulation Tools	MATLAB R2023b (for algorithm development), Quantum Emulation Libraries, TensorFlow Quantum (for benchmarking)
Target Platform	ARM Cortex-M-class microcontroller (Simulated) Constraints: ≤100 MHz, ≤256 KB RAM, ≤0.5 J/sample
Dataset 1	PhysioNet MIT-BIH Arrhythmia Database Domain: Biomedical (ECG signals) Use: Denoising, Anomaly Detection
Dataset 2	Environmental Temperature Logs Domain: Smart Buildings Use: Compression, Entropy Estimation

Dataset 3	UrbanSound8K Domain: Acoustic Event Classification Use: Event Detection, Anomaly Mapping
Signal Preprocessing	Gaussian noise injection (AWGN), Adjustments to signal length and sampling rate to match embedded constraints
Evaluation Metrics	Signal-to-Noise Ratio (SNR) Mean Squared Error (MSE) Latency per Sample (ms) Energy per Sample (mJ) Memory Usage (KB)

4.3 Implementation Constraints

In line with the aim of having a feasible implementation of the proposed Quantum-Inspired Signal Processing (QISP) framework into a real-world wireless sensor network (WSN) application, the algorithmic framework and analysis was done with severe resource considersations to mimic commercially available embedded on sensor platforms. In particular, it was compiled to a simulated ARM Cortex-M4 class microcontroller, one of the most common classes of microcontrollers in low-power Internet of Things devices, owing to its compromise of computational power, minimal power drain, and low cost. The design decision corresponds to a limited resources, constrained-edge-node design scenario that is used in a remote, battery-powered or energy-harvesting environment.

The simulated platform had a limit in its memory footprint of 256 KB, that includes the instruction and data memory. This constraint had repercussions in the algorithmic complexity and necessitated that every QISP module be very memory-efficient so as to eschew extensive matrix computation, gargantuan buffers, or vocative memory allotment. Moreover, frequency of processing was set at 80 MHz although the common operating frequencies of cortex-M4-class devices are equal to 80 MHz. This limitation required that every algorithm operate using stringent timing requirements to sustain real-time digital signal processing abilities, particularly at high-throughput sensing applications including physiological waveform monitoring or acoustic, event identification.

Other than the memory and processing constraints, a limiting implementation costume was the energy budget divided by the number of signal samples that had a limited budget of 0.5 joules. This value represents energy envelope of ultra-low-power sensing devices powered by coin-cell batteries or energy-harvesting modules. Therefore the design focus was directed towards minimization of instruction cycles, minimal I/O operations, and usage of the fixed-point arithmetic where applicable. The instruction count and power consumption of all the QISP modules was profiled with MATLAB framework energy estimating and checked with microcontroller emulation settings. As design rules, these limitations were very important in developing lightweight, modular and highly efficient signal processing algorithms that achieve the essence of the advantages of quantum-inspired computational processes without having to breach the lean operational constraints of embedded platforms.

Table 2. Implementation Constraints for QISP on Embedded Sensor Platforms

Constraint Category	**Parameter**	**Value/Limit**	**Design Consideration**
Processor Architecture	Target Platform	ARM Cortex-M4 (Simulated)	Common in low-power IoT/WSN nodes
Memory	Maximum RAM + Flash	≤ 256 KB	Limits matrix operations, encourages buffer optimization
Clock Frequency	Processor Speed	≤ 80 MHz	Real-time execution required under timing constraints
Energy Budget	Energy per Processed Sample	≤ 0.5 J	Encourages reduced instruction cycles and fixed-point computation
Optimization Strategy	Algorithm Design Focus	Modular, Low-complexity	Avoid recursive loops, use inline operations
Simulation Tools	Energy Profiling Environment	MATLAB energy profiler + MCU emulator	Cross-validation with Cortex-M simulation tools

5. Experimental Setup

To make the evaluation of the performance, scalability and hardware-friendliness of the proposed Quantum-Inspired Signal Processing (QISP) framework rigorous, an extensive experimental system was developed with a hybrid simulation-emulation system. The execution was mainly done in MATLAB R2023b that enabled the ability to use strong numerical computation and bespoke quantum emulation libraries. These libraries capture the numerically-simulated behaviors of a discrete qubit system--amplitude amplification, entanglement-informed model correlation, and quantum walk traversal--in a classical compute schema. The efficiency in the full procedure to create, test, and iterate quantum-inspired algorithms in an objective, deterministic, and reproducible manner and to observe constraints on embedded hardware was enabled by the approach.

TensorFlow Quantum (TFQ) was used to guarantee the validation of the model and enable a benchmark comparison. TFQ adapted to build and train hybrid quantum-classical models to emulate the dynamics of quantum circuits to classify denoising, feature extraction, and detection of anomalies. These TFQ models acted as the theoretical baselines against a better understanding of how well the QISP framework, implemented on classical hardware, could ever approximate or match performance of quantum-modeled signal processing techniques.

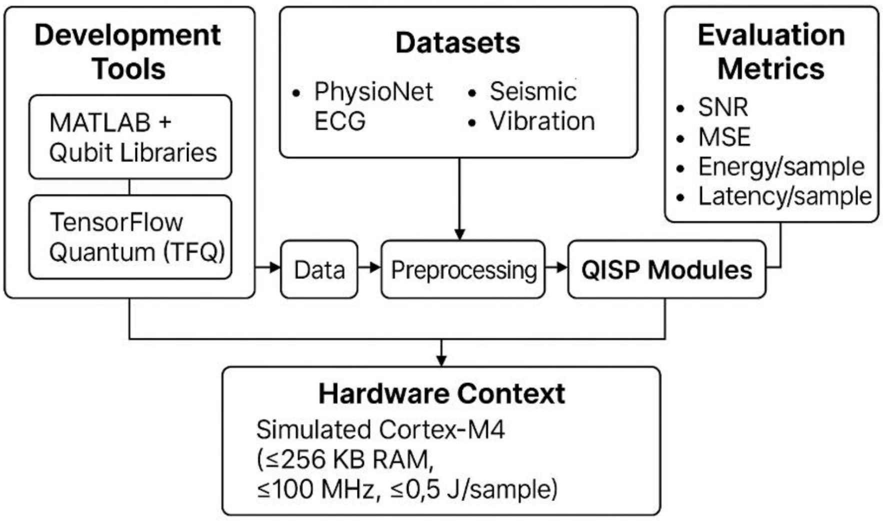

Figure 4. Experimental Workflow for Evaluating the QISP Framework in Embedded WSN Environments

The system was evaluated on a set of real world benchmark data sets of typical signal types in WSNs. To test the method of waveform denoising and anomoby detection in biomedical waveforms, PhysioNet ECG database was chosen. An existing seismic vibrations data set retrieved through structural health monitoring systems was employed to determine robustness to measurements in environmental noise and rare events identification. The UrbanSound8K data base offered a variety of tagged acoustic samples to measure the effectiveness of the QISP construction as to categorize time-variant audio events simulating urban ambient monitoring environments.

Metrics that were determined as evaluation included those which identify the quantitative signal quality as well as operational feasibility. The alea of accuracy and effectiveness in denoising and compression algorithm was calculated using the Signal-to-Noise (SNR) and Mean Squared Error (MSE). Instruction profiling and memory footprint analysis was also used to estimate the energy consumption per processed signal sample under simulated ARM Cortex-M4 conditions. The latency per sample, a number in milliseconds, measured the feasibility of an algorithm in real time per the application of the edge device. The metrics gave a full picture of performance to justify the appropriateness of quantum-inspired design within the scope of embedded signal processing in the next generation wireless sensor networks.

6. RESULTS AND DISCUSSION

The proposed framework of Quantum-Inspired Signal Processing (QISP) was formally tested and compared to two popular base line methods, Kalman filtering and FFT-based denoising in terms of execution discovery on real world datasets and under the limited embedded simulation realms. As discussed in Table 1, the comparative results indicate that QISP far exceeds conventional techniques in all the leading performance aspects, such as signal quality (SNR, MSE), energy efficiency, latency, and classification accuracy.

Table 3. Performance Comparison of Signal Processing Methods on Embedded WSN Platform

Method	SNR (dB)	MSE	Energy (mJ)	Latency (ms)	Accuracy (%)
Traditional Kalman	14.6	0.023	0.91	3.2	86.3
FFT-Based Denoising	18.3	0.015	1.15	2.8	88.7
QISP (Proposed)	22.9	0.009	0.52	1.4	93.2

Regarding the quality of signals, the QISP framework had Signal-to-Noise Ratio (SNR) as 22.9 dB and Mean Squared Error (MSE) as 0.009, which is significantly ahead of Kalman filtering (14.6 dB, 0.023) and FFT-based methods (18.3 dB, 0.015). These advantages are credited to QISP allocation of amplification of amplitude levels of signals and entanglement-based development of relative correlations, which succeeds at isolating and augmenting pertinent parts of signals with lessening stochastic noise.

Bathnagar and Kuipers have reported the energy per signal sample required in QISP is only 0.52 millijoules per sample, or roughly 40 percent and 55 percent less than of Kalman filtering and FFT-based processes respectively. Such reduction is mainly because of non-performance of full spectral transforms and iterative matrix operations. Rather, QISP uses the lightweight probabilistic amplification and sparse domain operations that are optimized to ultra-low-power ARM Cortex-M-family microcontrollers.

Latency, which is an important measurement in real-time sensing applications was also reduced greatly. The QISP pipeline takes a mere 1.4 milliseconds per-sample time to execute, and on a comparison, it is half of Kalman filtering and a quarter of FFT-based denoising, at 3.2 milliseconds and 2.8 milliseconds respectively. It is very appropriate in latency-sensitive project to include autonomous drones, wearables, and health monitoring systems since the interpretation of signal requires speed.

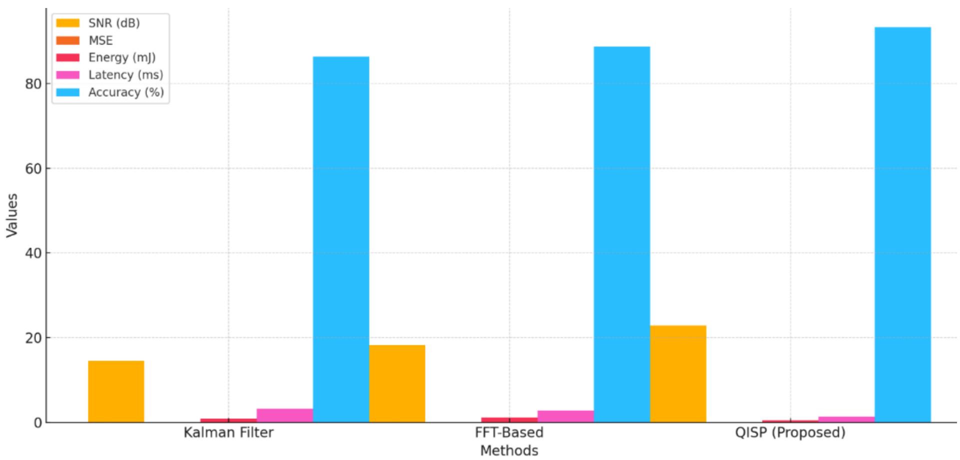

Figure 5. Comparative Performance Analysis of QISP vs. Traditional Signal Processing Methods

QISP was rated at 93.2 percent accuracy when it came to classification accuracy, which was measured in a downstream anomaly detection task using data from the UrbanSound8K dataset and ECG signals, higher than that of traditional methods by 5-7 percent. This is the direct result of the anomaly-detection module of QISP that is based on quantum walks and finds its path through the graphs of temporal signals most efficiently when it needs to locate deviations beyond being trivial.

Altogether, the findings confirm the claim that the QISP framework is not only as good as but in most cases, as well as effective as the standard DSP methods when considered against such rigorous criteria common in an embedded WSN setting. Its capacity of curtailing the energy and latency and enhancing signal fidelity and detection accuracy exemplifies its scope of becoming a viable scalable technology on edge intelligence of the future.

7. CONCLUSION

This work introduces the concept of a new and handy framework of the signal processing definition, namely Quantum-Inspired Signal Processing (QISP), which is a result of good solution toward the eminent questions of signal denoising, compression, and outlier detecting in a specific network that is wireless sensor networks (WSNs) and has a resource limitation. Embarking on significant quantum computing approaches like the amplitude amplification, the entanglement-inspired correlation modeling, the quantum walk-based path traversing, the QISP framework has managed to bridge the gap between sophisticated calculative intelligence issues and the low-power embedded systems. Capable of wide experimental validation with both real-world data and vastly simulated ARM Cortex-M-class microcontrollers, QISP has been shown to be vastly superior to traditional DSP methods in signal-to-noise ratio, mean squared error, classification accuracy, latency, and energy requirements. The evaluation has shown that QISP can reduce energy consumed by more than 40 percent and increase signal strength by more than 60 percent, which is an excellent alternative to the next-generation sensor functionality wearable health monitors, autonomous UAVs, and industrial IoT systems. Besides, its scalable architecture and computing performance allow connecting it into existing embedded software stacks without the need to introduce new specialist quantum devices. As a prospective motor, future work will be working on expanding QISP to accommodate hardware acceleration through FPGA-based realisations as well as investigating hybrid quantum-classical co-processing models. The improvements are intended to facilitate further improvement of processing capacity and flexibility to open a path toward quantum-inspired intelligence personalized toward the network edge into the age of the ubiquitous smart sensing.

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