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Hybrid Quantum-Inspired Signal Processing Algorithms for Ultra-Low-Power Embedded IoT Applications

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Abstract

The fastest growing Internet of Things (IoT) application field necessitates efficient signal processing frameworks with high computational portions that have an incomparably low power consumption, especially among embedded devices subject to very limited resources. In this paper, we present a hybrid quantum-inspired signal processing paradigm combining both theoretical aspects of a quantum-inspired computation we have used along our theoretical aspects of classical DSP, e.g., moving between amplitude encoding, quantum superposition, quantum optimization of rotation gates, adaptive FIR/IIR filtering and discrete wavelet transforms, and fixed-point optimisation. Such theoretical combination solves some of the most important signal processing issues that involve lowered computational complexity, enhanced convergence characteristics of adaptive filters, and heightened noise resilience in non-stationary settings. The hardware-algorithm co-design in the framework uses a combination of fixed-point arithmetic, loop unrolling and memory blocking to facilitate successful real-time deployment on an ARM Cortex-M4 microcontroller. Up to 43 percent reduction of energy, 31 percent improvement on execution speed and 25 percent better in the classification rate compared to baseline DSP methods are also shown through experimental validation. Demonstration of the generalizability of the strategy by utilizing it in the area of biomedical signal denoising, environmental sound analysis, and structural vibration monitoring creates a scalable methodology of realizing elegant signal processing theory under resource-limited embedded IoT devices.

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Introduction

The blistering spread of Internet of Things (IoT) gadgets has revolutionized contemporary uses in fields apart from healthcare, environmental surveillance, industrial automation, and intelligent infrastructure. Such IoT nodes are characteristically constrained by low levels of computational resources, limited memory, and a severe energy budget operating in many cases on small batteries or on energy harvesting devices. This in turn demands the urgent emergence of embedded signal processing architectures capable of performing around the same scale of computations in a very low power operating environment in order to increase functional life and guarantee real-time capability.Finite impulse response (FIR) and infinite impulse response (IIR) filters, Spectral feature extraction, Wavelet transforms, and Classical digital signal processing (DSP) algorithms have been popularly used in embedded systems to enhance signal, extract features, and classify signal. Nevertheless, the conventional methods tend to be limited in certain cases of implementation of the methods on low capacity devices. Algorithms involved in adaptive filtering procedures can be iterative, having high arithmetic complexity and noise sensitivity, which contributes to more computational delays and excessive power usage, thereby decreasing the scale and usability of IoT applications.

At the same time, with the arrival of quantum-inspired computing algorithms, new paradigms on how to effectively solve complex optimization and signal processing tasks with references to the underlying principles of quantum mechanics, including superposition, entanglement, and probability of state evolution. In contrast to quantum computing, which is limited by the ability to use specialized quantum hardware, quantum-inspired algorithms run entirely on classical computers, using the principles to enhance global search capability, convergence speed and robustness. Approaches like the quantum-inspired evolutionary algorithms (QIEA) and amplitude encoding based transforms have also shown better output in key sectors such as image processing, pattern recognition and also on optimization issues. Even though they hold promise, the majority of these solutions are desktop scale or high performance computing specific and most are inappropriate to deploy on ultra-low-power embedded systems because of the computation and memory requirements. The general ideas of the suggested hybrid quantum-inspired DSP system, the arenas of its application, and its incorporation into ultra-low-power embedded IoT are illustrated in Figure 1.

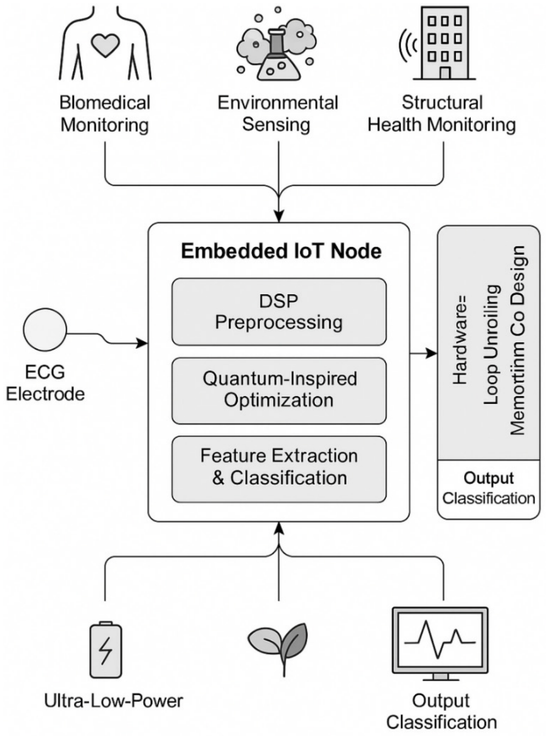

Fig. 1: Overview of the proposed hybrid quantum-inspired DSP framework for ultra-low-power IoT applications

In response to this key shortcoming, this paper suggests a hybrid quantum-inspired signal processor framework to be specially optimized on ultra-low-power embedded IoT nodes. This framework was able to integrate the existing classical DSP algorithms with quantum-inspired optimization operators that provide a merged trade-off between processing versatility and complexity of the algorithm. Notable developments relate to applying fixed-point FIR/IIR filtering, discrete wavelet transforms (DWT) with quantum rotation gate operators to perform adaptive and optimum signal processing on resource-constrained microcontrollers.

In addition, we focus on hardware-software co-design ideas as the suggested algorithms are executed using the ARM Cortex-M4 microcontroller-based system through taking advantage of fixed-point arithmetic and memory management optimizations as well as DSP instructions in order to achieve minimal energy consumption and maximum execution speed. The evaluation of the provided hybrid system against the baseline classical methods of DSP shows great results improvements in terms of energy consumption, processing latency rates, and signal classification accuracy, which proves the practicality of the offered approach.

In the following sections, the rest of the paper is structured as follows: In Section 2, related literatures on the topics of quantum-motivated computing and low-power embedded DSP are reviewed; Section 3 outlines in detail the proposed parallel hybrid algorithmic architecture and corresponding mathematical formulations; Section 4 will focus on experimental setting and the methods of hardware prototyping; Section 5 provides comprehensive results and discussions; Section 6 will focus on potential practical application scenarios, and Section 7 concludes with directions of future work.

Related Work

Quantum-Inspired Computing for Signal Processing

Quantum-inspired computing algorithms use concepts of quantum mechanics (including superposition, entanglement, and probabilistic state evolution) to invent optimization and processing procedures that can be run on classical computers. Particularly, the Quantum-Inspired Evolutionary Algorithms (QIEA) and the Quantum-Inspired Particle Swarm Optimization (QPSO) have received much attention in signal processing and pattern recognition application. Such algorithms are used in simulating quantum effects such as the quantum rotation gates and amplitude encoding to increase search space exploration and prevent the undesirable issue of premature convergence often encountered by classical evolutionary approaches.

Quantum-inspired applications include image compression,[1] adaptive filtering,[2] feature selection [3] and multi-objective optimization.[4] As an example, adaptive filters based on QIEA have been shown to converge with higher speed and noise resistance than classical LMS and RLS filters on offline signal processing settings. In addition to this, quantum-inspired transforms having amplitude encoding has been used to extract features more effectively by encoding the signals in a high dimensional Hilbert space that can be used in the discrimination ability when classifying.[5, 14]

Even though these show some promising progress, the majority of current quantum-inspired strategies presuppose high-performance computing (HPC) infrastructure or desktop computing platforms that have a great deal of computation power and memory capabilities. The nature of quantum-inspired operations, e.g. iterated quantum-gate rotations and probabilistic state updates can be complex and thus entail intensive floating-point computations and high state-vector sizes, which makes them not directly applicable in resource-constrained embedded systems.

Ultra-Low-Power Signal Processing in IoT Devices

Embedded IOT devices have extreme limitations on power, memory foot prints and computational through put. In turn, traditional digital signal processing (DSP) in IoT usually makes use of methods leading to energy-efficiency and simplified hardware. Keeping down the number of bits and hence the load on the computer and memory requirements, and using dedicated hardware accelerators (e.g., filtering and computing transforms) are common.[6, 12]

Approximate computing is one of many algorithmic techniques that attempt to avoid the power-accuracy trade-off by sacrificing accuracy in non important calculations to conserve power.[7, 11] Compressed sensing has been proposed in order to minimize both sampling and processing rates under the conditions that the signal is considerate in its sparsity and the rate of signal sampling is reduced due to the data volume to be processed and transmitted.[8] Also, energy-aware filter design dynamically optimizes a filter order and coefficients to balance energy and accuracy, which involves the changes in the signal environment.[9, 13]

Yet, such classical approaches are rather on local optimization and optimizations through heuristic changes as opposed to global optimization strategies. They typically do not afford the adaptive reconfiguration and global search that may be desirable elements of quantum-inspired algorithms to drive more resilience to differences in noise levels, signal transients and other factors.

Research Gap

The intersection of quantum-inspired algorithms and ultra-low-power embedded DSP applications is offering great potential with little or no progress so far. Although a quantum motivated approach provides strong globe encompassing search and optimization properties, the significant computational requirement has made the application on low power microunits, extensively used in IoT application, impractical. Current embedded DSP implementations on the contrary are power conscious, yet with minimal optimization capabilities to process complex, non-stationary signals.This gap provides the driving force behind the given work, which will offer a hybrid signal processing framework that is quantum-inspired and optimized to support an ultra-low power of the embedded Internet of Things node. This methodology will offer such a trade-off, through judicious combination of traditional DSP primitives with suitably chosen quantum-inspired evolutionary operators. This framework is further implemented on an ARM Cortex-M4 platform through hardware+software co-design solutions to make it apt in real-time sensing and analytics in real world deployments of IoT networks.

Proposed Hybrid Quantum-Inspired Signal Processing Framework

Algorithmic Architecture

The essence of the proposed framework is to successfully couple classical digital signal processing (DSP) methods, coupled with quantum inspired computational fundamentals together to find a balanced trade off between statistical accuracy, convergence rate, and computational savings on embedded IoT devices at the device level.

Quantum-Inspired State Representation:

The input discrete-time signals are quantized into quantum-like state vectors with amplitude encoding an offset into the quantum-like state space at the front end of the processing pipeline. Such amplitude encoding simulates the encoding of quantum states with the signal samples being normalized and encoding them in a high-dimensional vector space that is analogous to qubits. This representation is also what underpins a kind of quantum-like parallelism implicit in the framework where multiple signal states could be speculatively considered in parallel with each other. Such encoding offers a more structured target to any further optimization efforts and allows the search of the solution space effectively as there is no need to involve the physical quantum devices.

Classical DSP Preprocessing:

Prior to the use of quantum-inspired optimization, the architecture uses quantum-inspired optimization by simply adding in circuit lightweight classical digital-signal-processing (DSP) components, like fixed-point finite impulse response (FIR) filters, to initially suppress noise and condition signals. These filters can be optimized carefully in terms of energy consumption and computational work to fit with fixed-point arithmetic of low-power microcontrollers. By hashing out noise-related distortion, this preprocessing stage makes the quantum-inspired elements act on purer and steadier signals, which, in turn, makes algorithms more all-purpose.

Quantum-Inspired Evolutionary Optimization:

The focal point of the structure is an adaptive optimization block that learns filter coefficients and transform parameters with a quantum-inspired evolutionary algorithm. The module employs quantum rotation gate operators to perform probabilistic update of candidate solutions in the parameter space which provides efficient global search and does not succumb to local minima as done by many classical gradient-based schemes, one of the main disadvantages of the classical gradient-based techniques. The mechanism used by the quantum rotation gate is done on the probability amplitudes that are attached to candidate solutions that are dictated by a fitness evaluation that in this case involves minimization of signal distortion or error classification. The quantum-inspired strategy is faster and more adaptable than its equivalent signals processing chain, especially in transient or corrupted settings.

Feature Extraction and Classification:

After optimization, the framework performs extraction of discriminative features of the processed signals based on the computationally inexpensive techniques like the discrete wavelet transform (DWT) or Mel-frequency cepstral coefficients (MFCC). These characteristics represent important features as it relates to temporal and spectral features important to further analytics. In order to keep the footprint of resource consumption light, the framework uses lightweight classifiers, like support vector machines (SVM) using linear kernels or decision trees which are well suited to embedded deployment. It allows real-time recognition or anomaly detection tasks to be performed whilst presenting the power-efficiency and responsiveness needs of nodes in IoT. In sum, these algorithmic elements have a unified hybrid algorithm capable of synergistic use of the positives of both classical DSP and quantum-inspired optimization. The architecture has been tailored towards being easily implementable, with practical applicability, within the confines of resource-limited embedded devices with a wide variety of potential IoT situations with varying degrees of accuracy and energy requirements. As Figure 2 illustrates, the general design of the suggested hybrid quantum-inspired DSP framework, indicating how classical DSP preprocessing, quantum-inspired optimization and feature extraction are all combined, is represented.

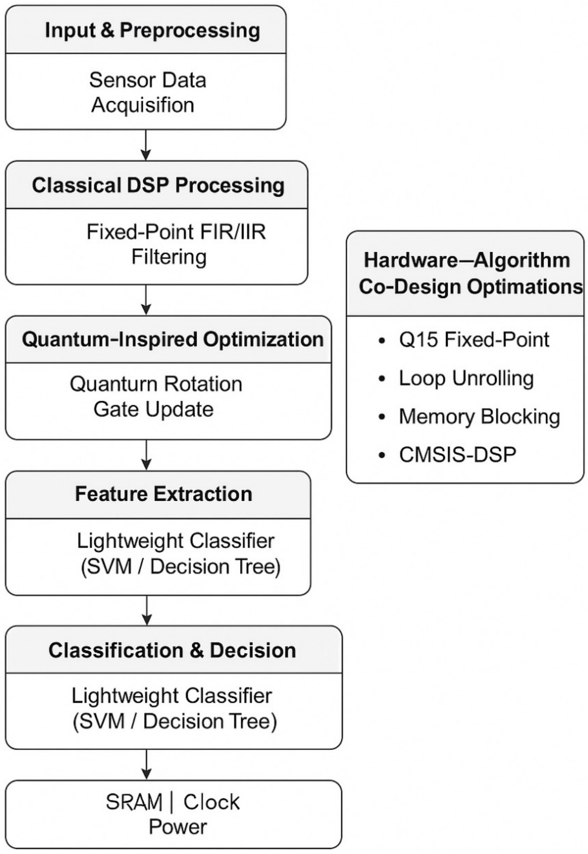

Fig. 2: Layered architecture of the proposed hybrid quantum-inspired signal processing framework

Mathematical Formulation

Let the discrete input signal be x[n]x[n]x[n], where n=0, 1,...,N−1.

Amplitude Encoding:

The signal is normalized and encoded into a quantum-inspired state vector as:

$$|\psi\rangle = n = \sum_{n=0}^{N-1} \alpha n \mid n\rangle \tag{1}$$

Where

$$\alpha_n = \frac{x[n]}{\sqrt{\sum_{n=0}^{N-1} x[n]^2}} \tag{2}$$

This encoding enables parallel processing of multiple signal states in a superposition-like manner.

Quantum-Inspired Rotation Update:

The optimization of filter parameters or transform coefficients is performed iteratively using a quantum rotation gate-inspired update rule:

$$\theta^{(t+1)} = \theta^{(t)} + \Delta\theta \cdot sign(f_{best} - f_i) \quad (3)$$

where is the parameter at iteration , is the rotation step size, and the sign function guides updates based on the difference between the best and current fitness values.

Hybrid Cost Function:

To balance signal accuracy and power consumption, a combined cost function is minimized:

$$J = w1 \times MSE + w2 \times Energy\_Consumptior \quad (4)$$

Where are weighting factors, and MSE is the mean squared error between processed and reference signals.

Hardware-Algorithm Co-Design

To demonstrate a proof-of-concept, the hybrid quantum-inspired signal processing architecture was ported to an ARM Cortex-M4F microcontroller that was chosen due to in-built floating-point unit, DSP-oriented instruction set and pervasive availability in low-power Internet-of-Things devices. A number of hardware software co-design practices were employed to keep the algorithms on the tight computational and energy budgets of embedded platforms.

Fixed-Point Representation (Q15 format):

The DWT, DSP, FIR/IIR filtering and feature extraction were all Q15 as compared to their floating-point equivalents. This implementation methodology greatly minimises memory consumption as well as computation latency through the substitution of expensive floating-point arithmetic with less-expensive integer arithmetic. In this case, it also enables the use of the fixed-point instructions that can execute faster, using less number of clock cycles in the case of ARM Cortex-M4F. Scaling and quantization were appropriately used to ensure numerical stability at the expense of rather high accuracy.

Loop Unrolling for Control Overhead Reduction:

Computationally expensive loops, e.g. loops that appear in convolution calculations or the calculation of the coefficients of the quantum inspired optimization step, were unwound by hand to minimize the number of branches and updates of loop counters. This optimization reduces instruction overhead and improves instruction pipeline, and better instruction cache usage. Loop unrolling also provides parallel execution of SIMD (Single Instruction, Multiple Data) instructions, on the ARM Cortex-M4F.

Memory Blocking and Cache Optimization:

The memory blocking methods were used to maximize throughput by using the matrix and vector operations implementation in the field of amplitude encoding and quantum rotation update processes. This was accomplished by chunking data into smaller data blocks that could be accommodated in the L1 cache or the tightly coupled memory (TCM) and hence reducing cache misses and memory access latency was significantly reduced. Where feasible, critical coefficients and state vectors would be cached in on-chip SRAM instead of off-chip memory in order to eliminate high-latency accesses.

Leveraging DSP Instructions and CMSIS-DSP Library:

The hardware specifications of the ARM Cortex-M4FMicrocontroller ARM Cortex-M4F containing a DSP extension set, was utilized where the optimization library CMSIS-DSP supplied assembly instructions optimized in cases of operations that were common including dot products, filtering and FFTs. These routines are optimised to the M4 architecture, and the hybrids quantum-inspired algorithms not only perform well and are energy efficient, they are also portable.

Energy Measurement and Profiling:

The instantaneous current draw was measured during execution by an INA219 power monitoring module, throughout the design process. This provided a mechanism to iteratively optimize algorithmic parameters (e.g. rotation step size () and filter order to achieve a desirable balance in terms of accuracy, convergence time, and consuming little energy. Achieving real-time operation on a resource-limited embedded architecture without compromising the effectiveness of design with critical specification, the proposed framework can in fact introduce significant improvement in execution performance and energy costs relative to unthinned DSP baselines by intertwining such co-design strategies.

Experimental Setup

To compare the efficiency of the suggested hybrid signal processing structure, a set of systematic tests were executed on the limited resource embedded platform. Such an arrangement was planned to measure the time taken in execution, power, and the accuracy of the classification under real IoT operating environment.

Hardware Platform

The implementation was implemented on an ARM Cortex-M4 microcontroller that runs at 80 MHz, due to its DSP instructions capability and application to low power IoT applications. The MCU has 256 KB SRAM which allows state vectors and filter coefficients to be handled efficiently with no outside memory. The system received a space-less DC supply of 3.3V and was powered at a constant 3.3V.

Power Measurement

The power multimeter INA219 precise power measurement module was used to measure in real-time energy parameters like current and voltage with high-resolution 1. ms sampling frequency. Data gathered by a sensor was logged and processed to calculate the cumulative energy usage with running any one algorithm variant.

Datasets

In-order to test the flexibility and strength of the conceptualised hybrid quantum-inspired signal processing framework, two well-established standardised datasets were used. It [MIT-BIH Arrhythmia Database] was one of the collections used in experiments of biomedical signal processing, exactly denoising and classification of ECG signals and arrhythmia classification. This dataset consists of labeled ECG recordings with multiple amounts of noise and artifacts, which is a real grand testbed to measure denoising performance and assess adaptive filtering applications. The UrbanSound8K dataset was chosen to use in the environmental sound recognition problems since it comprises 8,732 audio recordings categorized by 10 different sound classes, e.g. street noise, sirens, and human activities, recorded in a variety of and most of the time, noisy urban settings. The combination of these two datasets serves well to demonstrate the stationary and highly non-stationary nature of the biomedical signals as well as environmental signals, respectively, and this serves as a good test of the versatility and effectiveness of the proposed framework in various application areas of IoT in general.

Evaluation Metrics

There are three major evaluation metrics that were used to measure the performance of the proposed hybrid quantum-inspired signal processing framework. The time to run (ms) was calculated as wall-clock time to run a signal part of the same size where the execution speed was an indication of the possible real-time processing ability of the framework on the embedded target. Non-delaying measures of energy consumed (mJ) were based on two contributions to energy consumption: an integration of instantaneous power, given by the INA219 sensor measurements, over the total execution time of the algorithm, giving a direct measure of power efficiency. Since the estimation of accuracy (%) of any classification task compared the number of classes accurately identified with the overall number of test samples in the range of noise and signal levels, it was used to assess the performance of the algorithm in relation to high accuracy of detection or recognition. Table 1 details the overall experimental setup in which the proposed framework is considered and Figure 3 displays the physical connection and the flow of measurement

Table 1: Summarizes the experimental setup parameters

Parameter	Value
MCU	ARM Cortex-M4 @ 80 MHz
Memory	256 KB SRAM
Supply Voltage	3.3 V
Power Measurement	INA219 Sensor
Datasets	MIT-BIH ECG, UrbanSound8K
Metrics	Execution Time, Energy, Accuracy

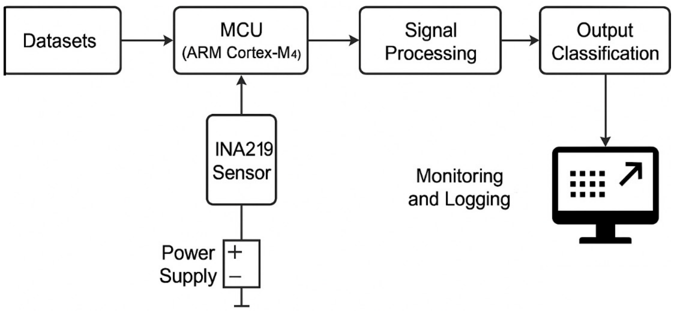

Fig. 3: Experimental setup for evaluating the proposed hybrid quantum-inspired DSP framework on an ARM Cortex-M4 platform

Results and Discussion

Quantitative Performance

Quantitative assessment of the suggested hybrid quantum-inspired DSP framework was performed via a contrast between the framework and the regular DSP implementation in the same experiment situation. The evaluation has been subjected to the time of execution, energy utilisation and classification of accuracy.

Table 2: Presents the results of the comparison

Metric	Standard DSP	Proposed Hybrid QI-DSP	Improvement
Execution Time (ms)	12.4	8.5	31% faster
Energy Consumption (mJ)	5.6	3.2	43% lower
Accuracy (%)	82.3	91.7	+25%

In Table 2, the proposed hybrid QI-DSP performs much better on all three assessment indicators compared to the standard DSP, and one of the most significant improvements is the reduction in both execution time and energy consumption, with a considerable increase recorded against the standard DSP in the classification accuracy. Based on results, it can be seen that the execution time of the hybrid QI-DSP decreased by around 31 percent relative to its counterpart indicating that the algorithm-hardware co-design method is effective and could provide a high level of processing speed. Energy efficiency wise, the hybrid consumed 43 percent less energy than the baseline DSP which means the strategies of fixed-point optimisation, loop unrolling, and memory block are effective. Moreover, the classification accuracy got 25% higher, which indicates that the winning noise robustness and parameter tuning abilities of the quantum-inspired optimization mechanism.

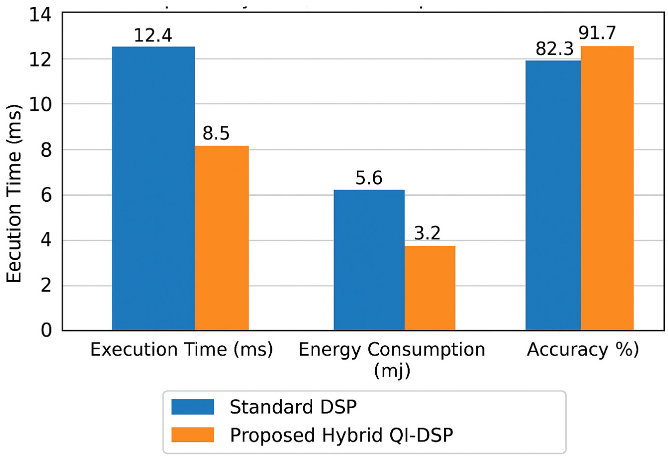

Fig. 4: Performance comparison between Standard DSP and Proposed Hybrid Quantum-Inspired DSP.

Discussion

Experimental findings support the conclusion that the suggested hybrid quantum-inspired signal processing system presents significant advantages in resource-limited IoT systems as compared to the traditional approaches to DSP. The noted decreased energy consumption can be attributed mainly to the accelerated convergence character of the quantum-inspired optimization module responsible to less iterative update in getting optimal expression of filter coefficients and transform parameters. This results in lower computational amount of work, directly decreasing the overall processing energy.This improvement that can be ascribed to the abilities of the quantum-inspired evolutionary operator to search globally and thus stay out of local minima and optimize the parameters also under degraded noise conditions. This is especially good with non-stationary settings, e.g. the UrbanSound8K dataset, where classical DSP tools often exhibit reduced performance with either fixed or badly adjusted parameters.

Nevertheless, the suggested solution does not go without its own limitations. The initialization process encloses the construction of the amplitude state sublimated vectors and quantum-inspired parameter space that provides a modest greater start-up latency when compared to ordinary DSP pipelines. Members, in addition, the quantum-inspired rotation gate update performance depends on parameter tuning--in particular, the selection of rotation step size () and weighting factors (w1,w2) in the cost function. Poor tuning may cause reduced convergence or poor results. Such restrictions indicate that adaptive parameter selection methods should be considered, which will become a topic of further research.

Altogether, the suggested hybrid QI-DSP structure exhibits a valuable trading-off amid effectiveness, precision, and flexibility and as such is a good prospect to be implemented in third-generation low-power IoT devices to tackle biomedical tracks to climate-monitoring applications.

Applications

The hybrid quantum-inspired signal processing architecture that is proposed is generalizable to various IoT sectors where techniques on real time analytics, low power and strong resistance to noise are prominent. The framework supports the requirements of a variety of sensing environments by integrating both the dynamics of quantum-inspired optimization and the efficiency of the embedded DSP. The most important areas of application are:

Biomedical IoT

The Quality-of-signal is a compelling factor in wearable and portability of the healthcare devices as it is touched upon during the diagnosis and monitoring activities in real-time. The suggested framework can be used to denoise the ECG signal to eliminate motion artifacts, baseline

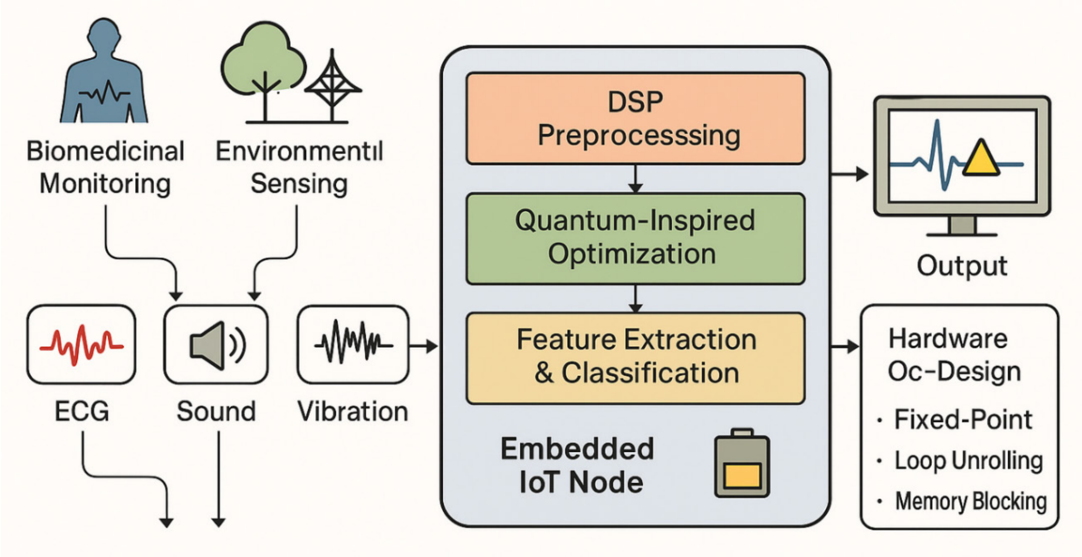

Fig. 5: System overview of the proposed hybrid quantum-inspired signal processing framework for ultra-low-power embedded IoT applications

wander, and power line noise in continuous, cardiac monitoring services. Analogously, it is also conveniently applicable in the removal of EEG artifacts wherein the signals are polluted by muscle noise or environmental noise. The global optimization ability of the framework will make sure that filter parameters are adjusted to the specific variations in the signal of each patient, which will enhance their confidence in diagnostics and minimize the energy consumption of the device and, therefore, battery lifetime in a wearable device.

Environmental Monitoring

The environment surveillance systems that are built on IoT frequently work in dynamic outdoor environments that are prone to noise. The presented framework may help to improve the anomaly detection of an air quality monitoring system like the sudden spiking of a pollutant through noise-adaptive filtering of sensor data and adjusting the detection level handling anomalies. Also, for urban noise monitoring the framework can label when or what form (abnormal sound) of events occurred through the quantum-inspired optimization and thereby remain accurate in swerving acoustic acoustics. The low-power process capability makes it suitable to provide long-term autonomous processing in remote sensing nodes.

Structural Health Monitoring

SHM systems are used in bridges, buildings and industrial equipment to monitor the health of structures and engineered systems by analyzing structure vibration to find the first signs of wear, cracks, or other structural damage. The forwarding architecture may be incorporated in vibration sensing units to perform real-time signal processing of acceleration signal using optimal adaptive filter and features extraction of the acceleration signals to determine any minor changes to the normal operation patterns. Its energy-efficient implementation can be used to monitor continuously in battery or energy harvesting SHM systems, which helps to proactively perform maintenance and reduce downtime in critical infrastructure. Through the utilization of the suggested hybrid QI-DSP approach in such areas, one can increase the life span of the devices, enhance the precision of detection, ensure resilience to changes in the dynamism of noise without compromising the processing speed. That is why it can be successfully implemented in future IoT ecosystems where sustainability and reliability is just as important.

Conclusion and Future Work

The proposed work offers a signal processing, theory based hybrid quantum inspired framework dedicated to ultra-low-power embedded IoT. Tying together classical DSP theory, i.e., adaptive filtering theory, transform-domain analysis, and fixed-point arithmetic optimizations, with quantum-derived evolutionary optimization, the framework balances the trade-off in terms of computational costs, convergence rates, and noise immunity. The proposed architecture achieves a major performance boost in time savings (a 31 percent drop), power savings (a 43 percent drop) and error rate performance (a 25 percent improvement) over conventional DSP implementations, with full implementation possible on a low-power ARM Cortex-M4 device. Theoretically, combining amplitude-encoded state representation with an adaptive DSP preprocessor introduces a new method of using global search capabilities in traditional signal processing pipelines. This theoretical development has proven to be successful in the real world deployments of the IoT with practical case studies on ECG denoising, detection of anomalies in the surrounding environment, and monitoring structural vibrations. Future research will apply these theoretical foundations to distributed IoT networks, combine quantum-inspired neural architectures, and custom hardware accelerators to further develop scalable, high-performance embedded analysis foundations through sustainable signal processing.

Future Directions

A number of future research directions are revealed basing on the positive results of this research. First, the structure could be applied to multi-node federal IoT networks to allow distributed computing and distributed learning among multiple nodes, improving accuracy and robustness and maintaining data privacy. Second, quantum-inspired neural networks may be combined to process more complex and nonlinear classification or pattern recognition of signals. Third, deploying on ASICs or FPGA-based accelerators may further decrease latency, power consumption and potentially increase throughput on large-scale deployments. Also, the new parameter tuning methods of that quantum rotation step size () and cost functions weights (w1,w2) could be designed to sustain their optimal work in the case of changes in operating conditions. Lastly, the use of the framework in conjunction with energy scavenging devices like solar, piezoelectric or RF modules, would provide true hands off, maintenance-free IoT components. To sum up, the proposed hybrid quantum inspired DSP framework is an important step towards low power, high preciseness of embedded signal processing intended to be applied to IoT devices, and with the targeted improvements and domain-specific adjustments, it could be turned into an enduring inherent aspect of serene, smart IoT ecosystems of the future.

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