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ENHANCED SINGLE-DIMENSIONAL WAVELET-DRIVEN ECGCOMPRESSION SYSTEM EMPOWERED BY A LOW-POWER SPIHT DECODER FOR QUALITY ASSURANCE

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Abstract

This paper introduces a novel Hardware Oriented SPIHT (Set Partitioning Hierarchical Trees) decoding algorithm tailored for the compression of electrocardiogram (ECG) signals. Traditional SPIHT structures, designed for images and videos, are resource-intensive and unsuitable for ECG com- pression. To address this, we propose an optimized SPIHT decoding algorithm that reduces memory usage and complexity. We also introduce a low-power hardware design for efficient implementation. Our goal is to create a cost-effective, real-time, and power-efficient ECG compression system tailored to portable applications, ensuring high-quality signal reconstruction.

Index Terms—SPIHT, ECG compression, portable applications, wavelet-based compression, Very Large-Scale Integration (VLSI), signal reconstruction.

I. INTRODUCTION

As the demand for mobile health (mHealth) applications continues to surge, integrating healthcare with mobile de- vices has become a paramount challenge and research focus. Among these applications, the measurement of electrocardiogram (ECG) signals holds a pivotal role. ECG signals,originating from the three-dimensional dynamics of the human heart, yield critical information when measured from multiple angles known as leads. These multi-lead ECG measurements are captured through biosensors placed on a patient's bodyand transmitted wirelessly via the wire-less body area network(WBAN) for storage and analysis.

The ECG signal that analysis the non-invasive method that offers valuable insights into a patient's cardiac health, aiding inaccurate diagnosis and minimizing diagnostic errors. However,to preserve the high-quality ECG signal data, uncompressed storage and transmission are typically required. This imposesa significant power consumption burden on mobile devices, which are often resource-constrained.

To address this challenge, the data compression of the wavelet-based ECG, particularly using the SPIHT coding scheme, has emerged as an effective solution. The 2D wavelet-based approach, leveraging the 2D DWT (Discrete Wavelet Transform), has shown promise in achieving a favorable balance between compressionratio and coding quality. Various methods have been proposed to optimize the coding process and enhance compression performance.

Nonetheless, the complexity and energy consumption associated with 2-D wavelet-based compression pose limitations on its feasibility for mHealth applications. Consequently, this paper introduces the data compression scheme with the quality-assurance 1D wavelet-based ECG, that achieved through SPIHT coding. This approach leverages modern state of the art Very Large-Scale Integration (VLSI) implementations, focusing on 1-D wavelet-based typologies.

While previous research has predominantly concentrated onimproving hardware throughput for 1D wavelet-based com- pression, has the coding qualities and quality on demand ECGdata compression have often been neglected. Furthermore, a corresponding SPIHT decoding implementation tailored for the proposed coding scheme remains underexplored in existingliterature.

II. LITERATURE REVIEW

A. Image Denoising Applications

1) Wavelet Approaches: Donoho and Johnstone initially introduced the concept of selective wavelet reconstruction, demonstrating its effectiveness when compared to other estimation methods. They developed SureShrink, a practical de- noising technique that adapts to spatial characteristics through wavelet coefficient reduction.

Chang and Vetterli proposed BayesShrink, an adaptive thresholding approach rooted in Bayesian principles, utilizing the generalized Gaussian distribution (GGD) as a prior for wavelet coefficients. Their method outperformed SureShrink in various scenarios.

Luisier's SureShrink, employing interscale orthonormal wavelet transforms, introduced a parameterized denoising process that minimizes mean squared error (MSE). This approach eliminates the necessity for specific [6] statistical models for wavelet coefficients, marking a significant departure from traditional methods.

This comprehensive review presents these contributions, emphasizing their unique strengths and limitations, and high-lights the evolution of wavelet-based thresholding methods in image denoising. It provides valuable insights for future research and applications.

2) Non-wavelet Approaches: Addressing noise in images is a fundamental challenge in image processing, with the goal of eliminating noise while retaining important image details. This article presents an extensive examination of significant progress in image denoising methodologies, highlighting the contributions of diverse researchers in this field.

Conventional approaches to image denoising often rely on spatial averaging, effectively removing noise but unfortunately introducing unwanted blurriness. To tackle this problem, neighborhood filters have been employed, taking into account the similarity of pixel gray levels before applying averaging. Buades conducted an in-depth analysis of neighborhood filters, demonstrating their equivalence to the Perona-Malik equation a pioneering nonlinear partial differential equation (PDE) used for image restoration. He proposed a simplified version employing linear regression to mitigate artifacts.

Kernel regression, another cutting-edge technique, draws in-spiration from nonparametric statistics. Take da adapted kernel regression for image denoising and related tasks, illustrating how various existing algorithms, including the bilateral filter, can be viewed as special cases within this[8] framework. Their iterative steering regression approach showcased superior performance in eliminating both Gaussian white noise and real- world noise.

This extensive review encompasses these pioneering contributions, offering insights into their strengths and limitations and providing valuable guidance for future research and prac- tical applications in the field of image denoising.

B. Blocking Artifacts Reduction

Mitigating compression artifacts presents a substantial challenge in the realm of digital image compression. This article conducts an in-depth examination of pioneering post-processing strategies geared towards alleviating compression artifacts. These methods hold a critical role in enhancing image quality following compression are: enhancement and the restoration techniques, often functioning within either the spatialor transform the domain.

The Enhancement based an algorithm strive to enhancequality without the explicit optimization, while restoration- based algorithms concentrate on the retrieval of the original image through optimization criteria. These approaches have found utility across various domains and are pivotal in elevating the visual fidelity of compressed images.

Apostolopoulos introduced an enhancement-based algorithm designed to identify blockiness and apply 1D and 2D median filters to diminish block disruptions and mosquito-likeartifacts.

Bovik proposed a swift and blind measurement approach in the DCT domain to identify and diminish blocking artifacts.A DCT-domain algorithm extracts parameters for blockingartifact detection, followed by a subsequent method that adaptively reduces the detected artifacts.

Lin devised a rapid algorithm for artifact reduction in the DCT domain, breaking down image vectors into signals[4] exhibiting gradual changes and fast variations. This approach effectively mitigates blocking and ringing artifacts while preserving image edges.

This comprehensive discussion thoroughly examines these post-processing techniques, emphasizing their merits, application areas, and the potential for future advancements in the realm of compression artifact reduction.

C. *Fast Bilateral Filter*

Bilateral filtering stands as a potent image enhancement technique, albeit with a potentially high computational burden.This article offers a thorough examination of inventive strategies geared toward expediting bilateral filtering, rendering it more efficient while upholding image quality. Such methods are indispensable in scenarios necessitating real-time processing and resource-constrained environments.

Paris and Durand introduced an approach that extends the bilateral filter by scrutinizing precision concerning bandwidth
and sampling. They established the bilateral filter's operation through filtering sub-sampled image copies[1] withdiscrete intensity kernels and then amalgamating outcomesvia linear interpolation.

Porikli introduced the constant time bilateral filtering method which is efficiently computes histograms for all feasible kernels within an image, capitalizing on spatial positioning. It facilitates the use ofvarious spatial kernels for bilateral filtering without escalatingcomplexity and expressed in the terms of spatial linear filter that applied into the original image's power.

Within the scope of this review, the framework integratestwo modules: one for identifying block disruptions and adjusting parameters and another for detecting local regionsmoothness and dynamically tuning parameters. These mod- ules augment the adaptability and efficacy of the bilateral filter. This comprehensive review encompasses these advancements, spotlighting their merits, limitations, and prospectiveapplications in image enhancement, thereby shedding lighton the ongoing research in the realm of accelerated bilateral filtering techniques.

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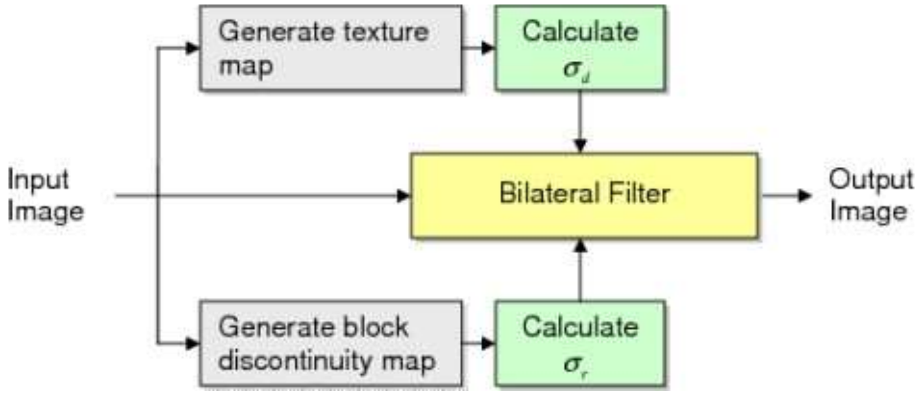

Fig. 1. Framework of adaptive bilateral filter

D. Parameter Selection

Bilateral filtering, a technique valued for enhancing images, often faces challenges in effectively addressing blocky arti- facts. This document introduces a fresh approach to enhance bilateral filtering by tackling the block discontinuities found within image blocks. Through the diffusion of these discontinuities from the block boundaries into the block interiors, the proposed method offers substantial improvements to the overall image quality.

To identify these block discontinuities, the input imageundergoes a specific filtering process along the block edges, using patterns such as [1, 0, 1] for vertical edges and [1, 0,1] for horizontal ones. The absolute values of the results arethen computed. Successful detection of discontinuities relies these values exceeding predefined thresholds. For an effective reduction of blockiness, it becomes imperative to extend the bilateral filter's application to cover the entire block.

This process of block discontinuity diffusion is carried out for all blocks, ultimately resulting in the creation of the block dis-continuity map, referred to as Mb(x). The paper also delves into the methodology of calculating the adaptive parameter r(x)and the discontinuity map block Mb(x) has been determined.

Fig. 2. The input image of compressed Lena, and the compression bit-rate is 0.18 in the Matlab.

The rmin value plays a crucial role as a controller, aiding us in finding a delicate balance between the standard bilateral filter's intensity filtering potency and the preservation of intricate image details. It's only when the estimated intensity parameter surpasses a specific threshold that it is deemedsuitable for employment as the intensity filtering parameter. This threshold-based approach effectively tackles compressionartifacts while safeguarding the overall image quality. The estimation of intensity parameter is only considered substantialif it exceeds a certain threshold.

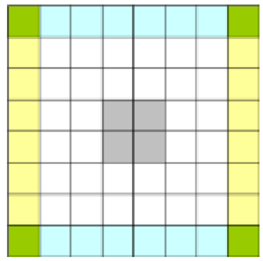

Fig. 3. Interpolation of the block discontinuities.

In order to identify regions of high frequency texture, that can calculate the standard deviation within the each of the block. This standard deviation serves as the indicator of the texture and guides the adaptation of the 'd' value to retain texture details. The accompanying figure can illustrate the standard deviation and calculated for each block withinthe compressed image Lena.

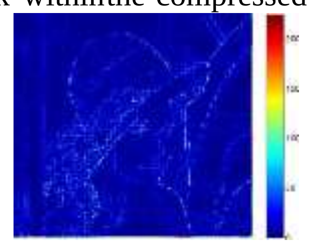

Fig. 4. Block discontinuity map

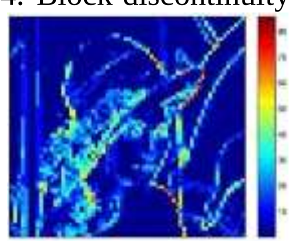

Fig. 5. The standard deviation for texture detection

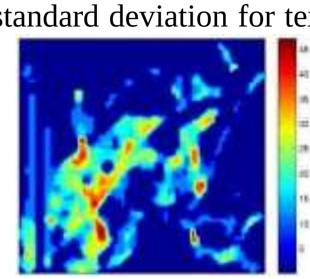

Fig. 6. The local Median filtered standard

It's important to note that the areas featuring edges and elevated standard deviation values are highlighted, indicating regions with distinctive textures. However, we also aim to apply a robust bilateral filtering approach to edge regions, ensuring the elimination of ringing

III. PROPOSED DESIGN OF SPIHT DECODING ALGORITHM

➢ ***RELATED SPIHT WORKS***

In here, we will provide a concise overview and examination of advanced SPIHT coding methodologies that are well-suited for data compression in wavelet-based systemsfor images, videos, and

ECG data. These approaches cater to both situations where quality is assured and situations whereit is not, and they find particular relevance in the context of mHealth applications.

1)The Quality-unassured the Data Compression method in SPIHT Coding:

It's representing the significant interest in the area development of high perform in the data compression system based on wavelets. Over time, researchers have introduced cutting-edge SPIHT designs, broadly categorized into two groups: one is list-based, non-list-based SPIHT designs.

List-based SPIHT coding entails two essential procedures: sorting and refinement, requiring three passes to facilitate these operations. However, this approach demands significant data storage and computational resources for sorting and refinement, and resulting to elevated the hardware complexity and sub-optimal performance. To address these issues, designers have implemented the hardware architecture reordering and optimization techniques to enhance speed, albeit at the cost of SPIHT coding quality. Consequently, suchdesigns are better suited for video and image compression rather than meeting the quality demands of ECG compression on-demand.

In contrast, the non- list based SPIHT encoder schemeis been proposed. Nevertheless, these approaches necessitate increased buffer sizes along the wavelet transform's decomposition layer and image dimensions, rendering them unsuitable for resource-constrained mobile devices in terms of cost and power efficiency.

To overcome these limitations and cater to real-time wavelet-based ECG compression systems with quality-on- demand requirements on mobile platforms, a novel SPIHT design that emphasizes coding efficiency and hardware optimization has been introduced, as depicted in Figure 1. Implementation results underscore its exceptional performance, low power consumption, and VLSI (Very-Large-Scale Integration)efficiency.

In this design, encoding side (highlighted into purple color)and consists of three primary functional blocks: Discrete Wavelet Transform, quantization, and loss-less SPIHT. The loss-less SPIHT code scheme is elaborated upon, with coefficients from 1D n-point Discrete wavelet transform and the quantization process serving as inputs to the lossless SPIHT encoder. These quantized coefficients are then organized into bit planes,encompassing sign and magnitude components.

Ultimately, this novel SPIHT coding algorithm achieves substantial reductions in register usage compared with the state art designs. It accomplishes this efficiency by eliminatingtraditional sorting and refinement processes, instead focusingon recording layer coding information and updating coding status. This approach not only simplifies hardware complexitybut also markedly accelerates the coding process, making itexceptionally suitable for real-time, power-efficient, and cost-effective wavelet ECG based compression systems designed for quality-on-demand scenarios on mobile platforms.

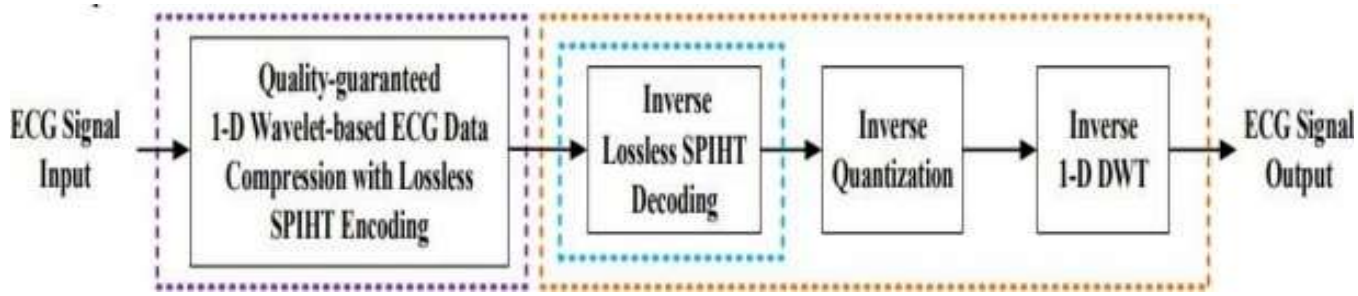

Fig. 7. Here the quality assured ECG compression system of Wavelet based system.

2)THE IMPLEMENTATION OF LOW-POWER HIGH PERFORMANCE SPIHT DECODER HARDWARE ARCHITECTURE:

In this section, we introduce the VLSIimplementation that innovative SPIHT decoding algorithm,which has been meticulously crafted to prioritize coding excellence, processing velocity, and power efficiency. This decoder design is precisely tailored to complement the cutting-edge approach of SPIHT encoding that relies on check-bitand status register files, making it particularly well-suited for wavelet.

Our decoder implementation embodies a holistic philosophy, harmonizing the essential facets of quality, speed, and power economy. It has been engineered to seamlessly decipherthe advanced SPIHT encoding technique, reliant on check-bit and status register files for peak performance in demanding applications such as ECG data compression.

Through this specialized decoder design, we ensure thatthe decoding process not only operates efficiently but also upholds the high coding standards requisite for precise ECG signal reconstruction. Furthermore, we've taken into account the imperative need for expeditious data processing, rendering it highly suitable for real-time applications. Moreover,our meticulous planning has encompassed power efficiencyto guarantee that the decoder functions optimally without excessive power consumption.

Initially, we embark on a comprehensive analysis of decoding algorithm was introduced in this research paper. Our objective is to thoroughly dissect the algorithm and subsequentlyformulate a VLSI hardware architecture meticulously tailored to its specific requisites. This meticulous planning phase lays the groundwork for the subsequent development of a high-performance, energy-efficient SPIHT decoding hardware architecture. Through a systematic design process, we engineer a hard-ware architecture that not only ensures exceptional decoding algorithm performance but also minimizes power consumption.

This synergy of high performance and low power consumption takes precedence in our architectural planning. Ultimately, our efforts culminate in the creation of real- time, cost effective, power efficient of the SPIHT decoder. This achievement is made feasible through our strategic utilization of favorable and straightforward of these hardware-oriented architecture, meticulously optimized to seamlessly accommodatethe distinctive demands of the SPIHT decoding algorithm.

As a result of this methodical approach, we successfully realize VLSI implementation of this

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proposed SPIHT decoder design, effectively demonstrating its performance. This design aligns seamlessly with our objective of achieving the real time, cost effective, energy efficient SPIHT decoder, ensuring its compatibility with the stringent requirements of modern data compression systems.

Our proposed SPIHT decoding design encompasses four integral coding units, each with a designated role in the decoding process. These units include the 1) CSIU, 2) BP TCU, 3) CS and BSDU, and 4) LDOU. This structured approach guarantees the systematic decoding of SPIHT-encoded data, divided into three mainsteps, with each unit handling specific tasks.

- Coding-Status Initialization Unit (CSIU): This unit is primarily dedicated to executing the functions outlinedin step 1 of the previous section. It plays a crucial role in initializing the coding status files for various components, including SCSF, and TBCSF. These initializations set the stage for subsequent decoding operations. Additionally, for efficient synchronization and timing considerations, the CSIU is strategically positioned within the same processing stage as the other units.
- Bit-Plane Threshold Calculation Unit (BPTCU): The BPTCU's primary responsibility is to calculate the thresh-old for each decoding layer. These thresholds play a vital role in determining which coefficients are significantand should be further processed during decoding. The calculated thresholds are essential for decoding efficiencyand maintaining the overall quality of the decoded data. [1] The input bit stream of SPIHT encoder is received from the BPTCU to facilitate this calculation.
- CS and CSBSDU: This unit is instrumental in performing the functions associated with step 2 of the previous section.
- The Lossless Decoding Output Unit: LDOUplays a crucial role in realizing the functions describedin step with the previous section. The output from the CSBSDU and processes it to generate the final lossless decoded output.
- This output is a reconstructed representation of the original data encoded using SPIHT.

This well-organized approach ensures efficient, accurate,and high-quality decoding of the input bit-stream.

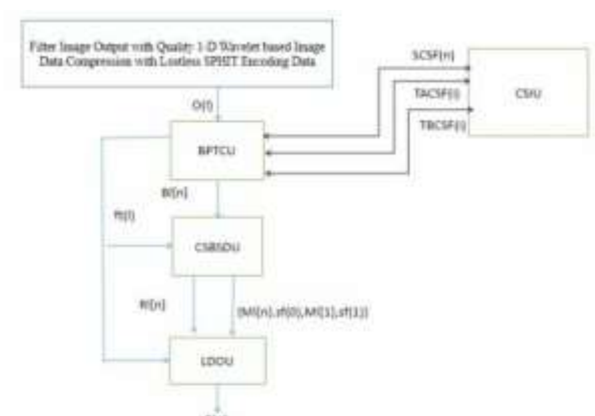


Fig. 8. Proposed Block Diagram Sphit Decoder

Within the confines of the CS and BSDU, the decoding procedure adheres rigorously to Algorithm Decode. This governing algorithm or chest rates the meticulous creation of the entire sub-layer decode bitstream, concurrently updating the 3 pivotal coding status files: SCSF, TACSF, and TBCSF. The hard-ware realization within the CSBSDU predominantly revolves around a singular Finite State Machine (FSM) entrusted with the task of overseeing decoding status. This FSM operates in tandem with comparators and shifters, facilitating the intricatedecoding operations.

Upon entry into the CSBSDU, the sub-layer bitstream becomes subject to the decoding regulations meticulously de- lineated in Algorithm Dec. These regulations serve as guiding principles, overseeing the generation of the complete lth sub- layer decoding bitstream with utmost precision and comprehensiveness. Moreover, as the decoding process advances, the coding status files undergo continuous updates, ensuring they faithfully mirror the latest decoding state.

Ultimately, the fully processed decoding bitstream, having undergone the CSBSDU's meticulous treatment, followsa sequential path into the Lossless Decoding Output Unit. Within the confines of the LDOU. It's note-worthy that this buffer has been thoughtfully designed with a specific capacity of 1.38 KB, precisely tailoredto accommodate the requisite data. Subsequently, the LDOU yields the ultimate decoding bitstream, denoted as C[n], afaithful representation of the fully reconstructed and decoded data.

This meticulous process ensures both the accuracy and efficiency of the decoding operation for the input bitstream, adeptly managing data storage and processing intricacies within the confines of the provided buffer size.

IV. EXPERIMENTAL RESULT

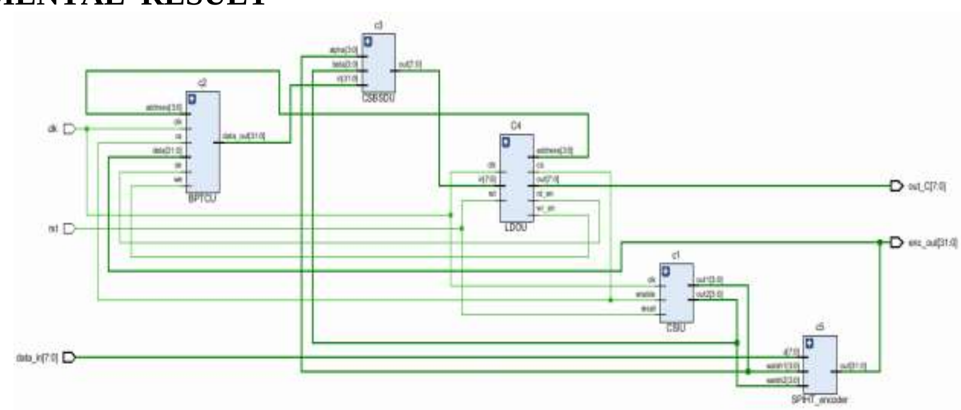
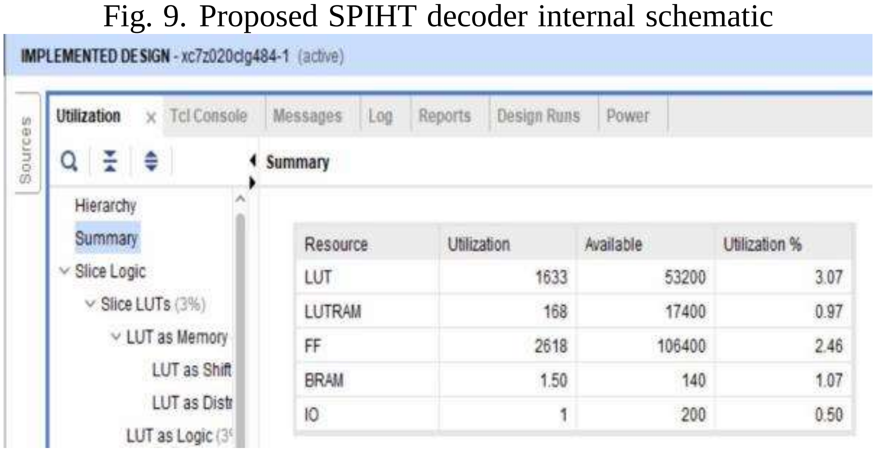


Fig. 9. Proposed SPIHT decoder internal schematic



Resource	Utilization	Available	Utilization %
LUT	1633	53200	3.07
LUTRAM	168	17400	0.97
FF	2618	106400	2.46
BRAM	1.50	140	1.07
IO	1	200	0.50

Fig. 10. Implementation summary

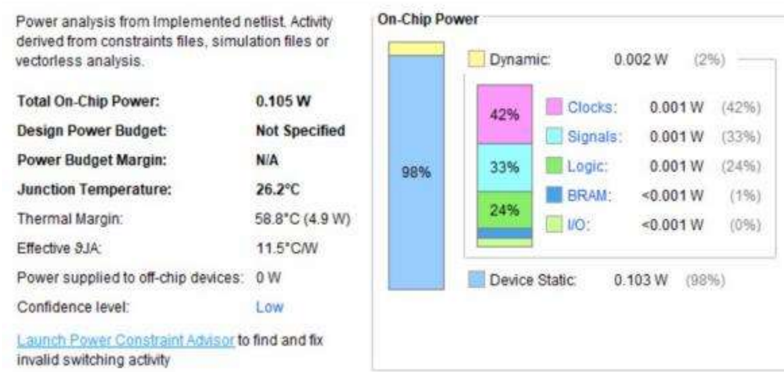


Fig. 11. Power

V. COMPARISON

Parameters	Existing design	Proposed design
Technology	Xilinx Vivado 2018.2	Xilinx Vivado 2018.2
LUT's	1907	1633
FF's	2409	2618
Technique	Bilateral filter VLSI architecture for image denoising	SPHIT decoder alogorithm performs encoding and decoding of image data input
Delay	7.826ns	5.483ns
Power consumption	0.109W	0.105W

Table 1. Comparison results for both existing and proposed method with respective parameters

VI. CONCLUSION

In summary, this manuscript presents a dual contribution: firstly, the inception of the SPIHT decoding algorithm coupled with its corresponding VLSI hardware architecture that places a premium on velocity and power efficiency within the realm of lossless SPIHT coding. Secondly, the efficacious realization and empirical validation of the SPIHT decoding VLSI blueprint, attesting to its aptness for quality- assured ECG compression system of wavelet-based in the context of mHealth. This investigation erects a robust underpinning for the evolution of data compression methodologies within the domain of medical applications and beyond, where the efficacious and top-tier data compression holds pivotal significance.

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