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VLSI ARCHITECTURE FOR DATA TRANSMISSION EFFICIENCY IN WSNs: INTEGRATING BAQ AND LEACH PROTOCOL STRATEGIES

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ABSTRACT
Wireless Sensor Networks (WSNs) are being increasingly utilized for real-time data collection and monitoring in remote areas with limited energy resources. Despite their usefulness, challenges such as energy efficiency and data transmission overhead persist due to the restricted battery life and bandwidth of sensor nodes. This paper details a groundbreaking VLSI architectural design that merges Block Adaptive Quantization (BAQ) compression with the LEACH (Low-Energy Adaptive Clustering Hierarchy) protocol to boost data transmission efficiency in wireless sensor networks (WSNs). BAQ effectively compresses data by quantizing blocks of sensor readings according to local data characteristics, while LEACH improves energy efficiency through adaptive clustering and role rotation among sensor nodes. The VLSI architecture has been crafted to lower power consumption, achieve high throughput, and support real-time capabilities, enabling data compression directly on the node before it is transmitted to the cluster head. Simulation results demonstrate substantial gains in energy efficiency, decreased communication delays, and enhanced hardware resource management. By merging BAQ with LEACH, this strategy not only conserves bandwidth but also extends the operational life of the WSN, making it well-suited for large-scale and long-term sensor network deployments.
KEY WORDS: Data Compression, BAQ, Leach Protocol, WSNs.

I. INTRODUCTION

Wireless Sensor Networks (WSNs) have become an essential component in a wide array of modern applications, such as environmental observation, industrial control, medical systems, smart farming, and military operations [4]. These systems consist of many small, energy-efficient sensor nodes that are strategically deployed across a specific geographic region. In WSNs a huge data transmission will be transmitted in network, handling such massive volumes of data creates significant strain on both bandwidth and power supply, particularly in multi-hop network configurations. Continuous raw data transmission is thus impractical for large-scale deployments. Reducing the volume of data transmitted over the network becomes vital to enhancing both reliability and longevity [7]. To address this, one of the most effective strategies is minimizing the number of bits transmitted. Data compression is a widely used solution for reducing data volume and conserving energy. Techniques such as Huffman encoding algorithm, Run-length encoding algorithm are conventional data compression techniques are employed to reduce transmission loads. Data compression transforms raw data into a more compact form. These methods can be implemented at sensor nodes or, more effectively, at cluster heads where temporal and spatial correlations can be exploited for greater compression efficiency. However, the performance of compression schemes depends heavily on the network's structure and communication protocols. Network topology—defining the interconnection pattern of nodes—

and routing protocols—determining the path of data flow—play a crucial role in data delivery efficiency and overall energy consumption, especially in Wireless Sensor Networks [5].

II. LITERATURE SURVEY

In recent years, extensive research has focused on developing data compression techniques to enhance energy efficiency and transmission performance in Wireless Sensor Networks (WSNs). Given the power and bandwidth limitations of sensor nodes, these methods are essential for efficient data handling. This survey reviews key conventional compression techniques and protocols, highlighting their strengths and limitations to support the development of more optimized, energy-aware solutions for WSN applications.

REVIEW OF COMPRESSION TECHNIQUES AND PROTOCOL

- **Transform-Based Compression Techniques:** Transform-based approaches, such as the Discrete Wavelet Transform (DWT), are extensively used for their ability to represent signals in both time and frequency domains. DWT decomposes a signal into multi-resolution sub-bands, capturing coarse and fine-grain information for effective compression. It is widely applied in signal and image processing due to its time-frequency localization and hierarchical structure, enabling efficient quantization and encoding [9].
- **Huffman Encoding:** Huffman coding is a lossless, variable-length entropy encoding method that assigns shorter codes to frequently occurring symbols. It relies on symbol frequency to build an optimal prefix tree, minimizing the average code length. Its integration into wireless systems has demonstrated reduced transmission energy, especially when combined with preprocessing techniques or adaptive models [10].
- **Run-Length Encoding (RLE):** RLE is a simple compression method that encodes sequences of repeated values by storing the value and its repetition count. Although less efficient for non-repetitive data, it performs well in scenarios with high redundancy, such as ECG signals and binary images. Its lightweight nature makes it suitable for low-power sensor networks [6].
- **Block Adaptive Quantization (BAQ) – “Kwok” and “Johnson”:** Initially introduced by “Kwok” and “Johnson” at NASA’s JPL, BAQ dynamically adjusts quantization thresholds based on the statistical characteristics (e.g., variance) of each data block. It is particularly effective for Gaussian-distributed radar signals and provides significant gains in compression efficiency by optimizing quantization on a per-block basis [7].
- **BAQ for Image Compression – “Monet” and “Meyer”**: “P. Monet” and “F.G. Meyer” extended BAQ principles for image data by dividing images into fixed-size blocks and applying adaptive quantization based on local energy levels. This block-based adaptation improves visual quality, preserves critical image features, and supports scalable compression with minimal side information, making it suitable for satellite and radar imagery [8].
- **Block Adaptive Quantization – “Lancashire”, “Barnes”, and “Udall”:** A further enhancement of BAQ was patented by Lancashire et al. for radar and sensor data with Gaussian noise profiles. The design features logarithmic lookup tables, exponent splitting, and efficient scaling mechanisms, reducing memory use and improving quantization performance. Its modularity

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supports high-s peed VLSI implementations, ideal for real-time SAR systems [2].

- **PEGASIS Protocol:** PEGASIS (Power-Efficient Gathering in Sensor Information Systems) improves upon LEACH by reducing the number of transmissions per round in WSNs. It forms a chain of sensor nodes using a greedy approach, allowing nodes to take turns transmitting data to a selected leader node, which forwards the aggregated data to the base station. This method lowers transmission overhead and balances energy use. However, its sequential nature leads to increased latency and requires complete network topology knowledge, limiting scalability [12].
- **TEEN Protocol:** TEEN (Threshold-sensitive Energy Efficient sensor Network) is a reactive protocol optimized for time-critical sensing applications. It introduces hard and soft thresholds to limit transmissions to instances when significant changes are detected in sensor readings. This approach conserves energy and supports rapid event detection. However, it is less effective for scenarios that demand regular or continuous data updates, as nodes remain inactive unless thresholds are exceeded [11].
- **LEACH Protocol:** LEACH (Low-Energy Adaptive Clustering Hierarchy) is a foundational clustering protocol that reduces energy consumption by dynamically forming clusters and rotating Cluster Heads (CHs). CHs gather, compress, and forward data to the base station, lowering communication load across the network. Its self-organizing structure enhances scalability and energy balance, though its random CH selection may lead to uneven energy usage over time [3]

III. PROPOSED METHODOLOGY

This work aims to develop a hardware-efficient system that integrates an improved Block Adaptive Quantization (BAQ) algorithm with the LEACH protocol to enhance data transmission efficiency in Wireless Sensor Networks (WSNs). By compressing sensor outputs using BAQ and employing LEACH for energy-aware routing, the system significantly reduces communication-related energy consumption. The methodology includes architectural design, modular hardware implementation, simulation, and performance evaluation, with a focus on scalability, low power, and practical hardware feasibility.

A. BLOCK DIAGRAM

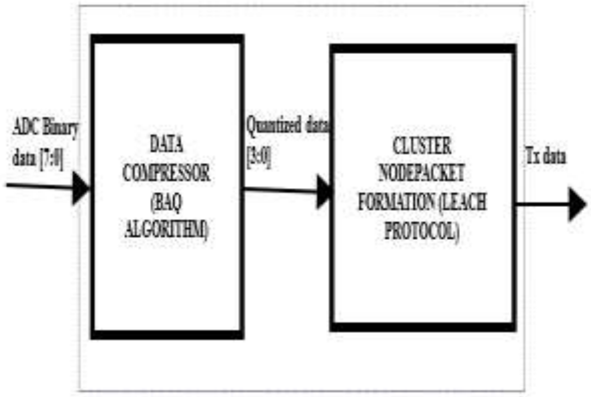

Fig. 1 Block diagram of proposed design

Fig. 1 presents the high-level functional block diagram of the proposed architecture that integrates Block Adaptive Quantization (BAQ) with the LEACH routing protocol for energy-efficient data handling in Wireless Sensor Networks (WSNs). The hardware design is fully pipelined and optimized for real-time sensor data compression and communication.

The architecture comprises two main processing units:

- **BAQ Data Compressor:** Receives 8-bit digital input from the ADC and compresses it into 4-bit quantized output using the BAQ algorithm. Key operations include exponent generation, LUT-based division, shifting, saturation detection, and quantization.

- **LEACH-Based Packet Formation:** Takes the compressed output and organizes it into LEACH-compliant packets. This unit manages clustering, TDMA scheduling, and cluster-head operations for efficient wireless transmission via the Tx_data bus.

B. SYSTEM ARCHITECTURE DESIGN

Fig. 2 illustrates the proposed system architecture, optimized for performance and hardware efficiency in WSNs. In typical sensor deployments, nodes collect environmental data and transmit it wirelessly, often under strict energy and resource constraints. To address this, the architecture integrates the LEACH protocol for clustering and routing, along with a hardware-embedded Block Adaptive Quantization (BAQ) module for in-node data compression at the cluster-head. The system begins with 8-bit digital input from an ADC (ADC_Binary_data [7:0]). This data is processed by the BAQ Compression Engine, which computes an exponent, selects a divide LUT, applies bit shifts, and compresses each sample into a 4-bit output.

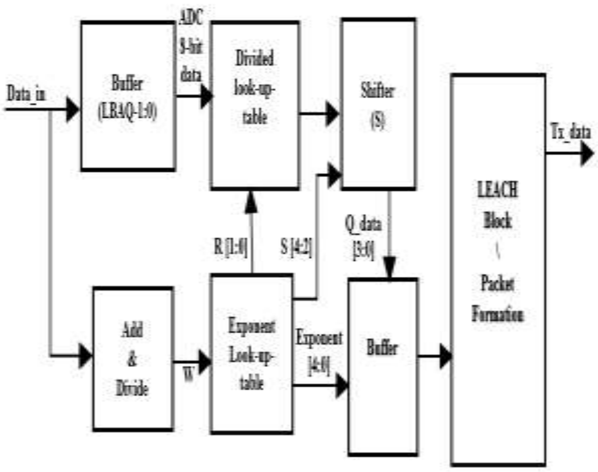

Fig.2 Architecture of proposed design

The compressed data is then forwarded to the Cluster Node Packet Formation Unit, which handles LEACH-based operations like TDMA scheduling, packet formatting, and base station communication. The final output (Tx_data) is a LEACH-compliant packet ready for wireless transmission.

C. BLOCK ADAPTIVE QUANTIZATION

The BAQ algorithm processes successive blocks of sensor data by computing an exponent value (E) for each block. This exponent is derived from the average or total of input samples and is used to normalize data via look-up tables (LUTs) and bit-shifting operations. The combination of logarithmically spaced LUTs and shift logic reduces table size and improves operational speed compared to conventional linear-spacing approaches. The Exponent formulae as follow as:

$$E = \mathrm{INT}\left[k \times \log_2\left(1 + \left(\frac{\sum_{N=1}^{LBAQ} |D_n|}{LBAQ}\right)\right) - C\right]$$

were

- k - constant,
- LBAQ - number of samples in a block,
- C - constant dependent on the extent of compression required

In this method, the 5-bit exponent E is partitioned into a 3-bit shift value (S) and a 2-bit remainder (R). R selects one of four divide LUTs.

$$\text{Output} = \mathrm{int}\left(\frac{ADC + 0.5}{R}\right)$$

Were

- ADC-refers to the data samples are stored in buffers,
- R-remainder (R_1, R_0)

while S controls the bit shift applied to the divided output. The result is a 4-bit quantized output that effectively compresses the input range. Code tables are grouped logarithmically—groups are spaced at 6 dB intervals, with each group containing four tables spaced at 1.5 dB—enabling more uniform fractional quantization across dynamic ranges. This structured compression allows scalable control over compression depth by selecting appropriate LUTs and shift values, making the system highly efficient for low-power hardware deployment.

D. LEACH PROTOCOL

LEACH, introduced by Heinzelman et al. [1], is a widely adopted hierarchical routing protocol aimed at minimizing energy consumption in Wireless Sensor Networks (WSNs). It clusters nodes to reduce long-distance transmissions and balances the communication load through dynamic cluster-head (CH) rotation.

Each LEACH round has two main phases:

- **Setup Phase:** This phase forms the cluster structure and includes three key sub-phases:
  - Advertisement Phase: Nodes independently decide to become CHs based on a probabilistic threshold and broadcast their status.
  - Cluster Formation Phase: Non-CH nodes select the nearest CH (based on Received Signal Strength Indicator) and send a join request.
  - TDMA Schedule Creation: The CH prepares a Time Division Multiple Access (TDMA) schedule assigning time slots to member nodes, minimizing collisions and idle listening.
- **Steady-State Phase:** Nodes transmit data during their allocated slots while staying in sleep mode otherwise to conserve energy. The CH aggregates and optionally compresses the data (e.g., using BAQ) before transmitting it to the base station.

By combining localized data fusion and scheduled communication, LEACH extends network lifetime and reduces overall power usage. However, it assumes static topology and uniform node distribution, which may limit its adaptability in more dynamic or large-scale WSNs.

IV. IMPLEMENTATION

The proposed BAQ-LEACH-based Wireless Sensor Network (WSN) architecture is implemented using a hardware-centric approach modelled in Verilog HDL. Emphasizing energy efficiency and real-time data reduction, the system integrates Block Adaptive Quantization (BAQ) at the cluster-head level and the LEACH protocol for hierarchical routing. The operational workflow is divided into the following key hardware-accelerated steps:

- **Step 1:** Data Collection (Buffer Fill): Sensor nodes acquire environmental data, digitized via an 8-bit ADC and temporarily stored in a FIFO buffer. A full data block (e.g., 64 or 128 samples) triggers the compression process.
- **Step 2:** Exponent Calculation: The average energy of the block is estimated to derive the exponent value, where $K = 4$ and $C = 8.5141$ for 4-bit compression, which is then split into:
  - Shift value (S): Upper 3 bits
  - Remainder value (R): Lower 2 bits
- **Step 3:** Divide and Shift: Each sample is processed using a divide Look-Up Table (LUT) selected based on R, followed by a right bit shift by S.

This scales the dynamic range of the data block.

- **Step 4:** Quantization: Scaled samples are compressed to 4-bit sign-magnitude format (3 bits for magnitude, 1 for sign), achieving significant data reduction while preserving key signal characteristics.
- **Step 5:** Non-CH Node Packet Transmission: Non-cluster-head nodes encapsulate the compressed data and exponent into a LEACH-compatible packet and transmit it during their TDMA-assigned slot.
- **Step 6:** Cluster-Head Aggregation and Transmission: Cluster-head nodes receive packets from member nodes, optionally perform re-compression or aggregation, and forward the final compressed packet to the base station in a single high-energy hop.

This design ensures scalable, low-power operation suitable for real-time WSN deployments.

V. RESULTS:

Fig.3 displays the simulation of 8-bit ADC data collection, representing the digitized sensor readings. Fig.4 presents the waveform of the 4-bit compressed data, confirming the effectiveness of the Block Adaptive Quantization (BAQ) module. Fig. 5 shows the simulation waveform of packet formation and data transmission from a non-cluster-head (non-CH) node to its respective cluster-head (CH). Fig. 6 demonstrates the cluster-head operation, displaying the collection of data packets from member nodes and final transmission to the base station (BS).

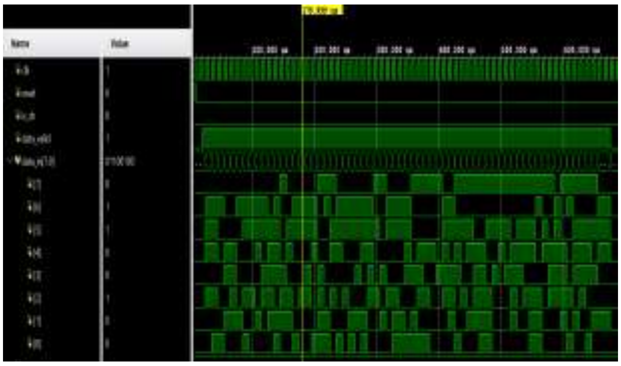

Fig. 3 8-bit ADC data have been collected

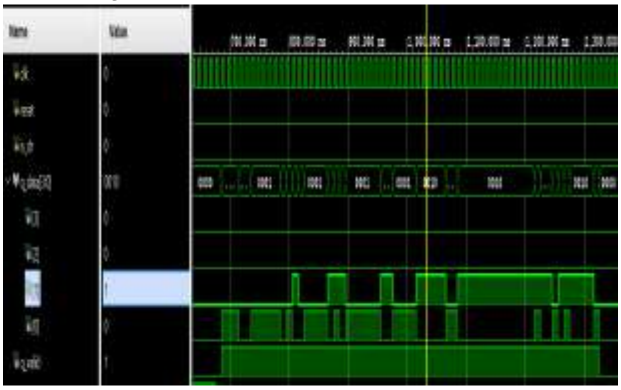

Fig. 4 Compressed 4-bit data

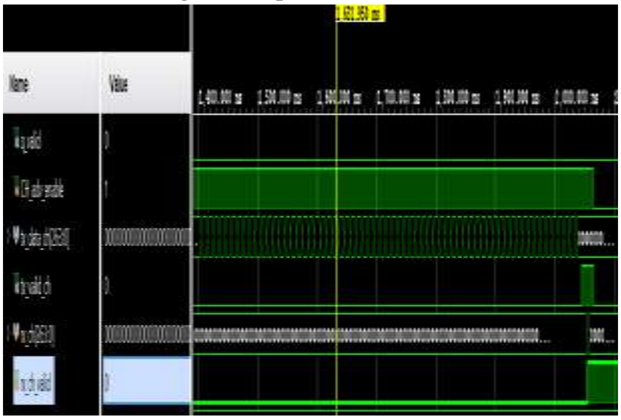

Fig. 5 non-CH node sent data to CH node

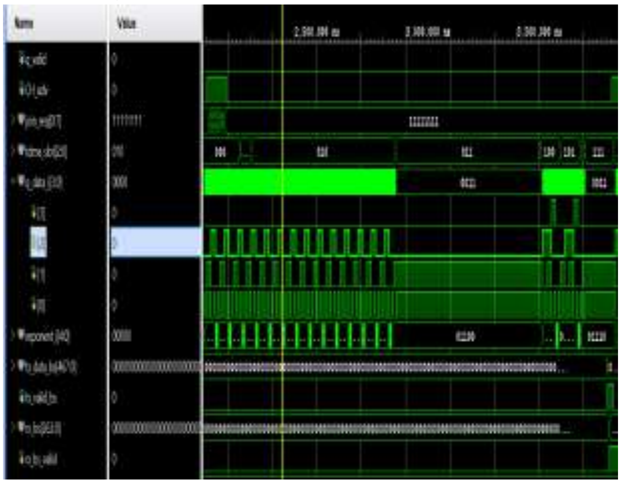

Fig. 6 Data packets sent to bs

A. OBSERVATIONS:

i. Bandwidth Usage Formula:

Bandwidth Usage=N*b

Were,

- N = no. of samples
- b = no. of bits per sample
- Original data bandwidth usage=512 bits.
- Compressed data bandwidth usage = 256 bits + 5 bits(exponent)
  Compressed data = 261 bits

ii. Compression Efficiency:

$$\text{Efficiency} = \left(1 - \frac{\text{Compressed Size}}{\text{Original Size}}\right) \times 100$$

Therefore, Compression Efficiency is 49.02%

B. COMPARASIONS

By simulating the proposed BAQ algorithm, a compression efficiency of 49.02% was achieved. This result demonstrates a significant improvement compared to conventional techniques, indicating better data reduction and enhanced energy savings for wireless sensor nodes.

SI. NO	Compression Method	Compressed Bandwidth (bits)	Compression Efficiency (%)
1.	Original (uncompressed)	512	-
2.	BAQ	261	49.02%
3.	Huffman encoding	352	32.25%
4.	Run-Length-Encoding	360	30.09%

VI. CONCLUSION

In conclusion, a hardware-efficient architecture integrating Block Adaptive Quantization (BAQ) with the LEACH clustering protocol was developed to enhance data transmission in Wireless Sensor Networks (WSNs). The design minimizes energy consumption by compressing sensor data before transmission and reduces bandwidth usage through effective data reduction. LEACH enables balanced energy usage via dynamic cluster-head rotation, while TDMA scheduling prevents collisions and idle listening. The combined approach demonstrates that data compression and hierarchical routing can be efficiently implemented at the hardware level, leading to reduced data size and prolonged network lifetime. Simulation and synthesis results validate its low resource utilization and suitability for low-power embedded sensor systems.

VII. FUTURE SCOPE

The current system performs well in energy efficiency and data transmission, but several enhancements can boost its practicality.

- Improving cluster formation with adaptive algorithms can increase stability in dynamic or uneven networks. Adding fault detection would enhance reliability in real-world scenarios.
- Moving from FPGA to ASIC could reduce power and size, making it ideal for large-scale or compact deployments.
- Real-world testing in environments like smart agriculture would validate performance beyond simulation.

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