Engineering Universe for Scientific Research and Management
ISSN (Online): 2319-3069
Vol. XVIII Issue IV
April 2026

A Comprehensive Review of Reversible Logic-Based Sequential Circuits for Low-Power Applications

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Abstract
In this paper, a review of reversible logic-based sequential circuits is presented for low-power digital system design. Reversible logic eliminates information loss, thereby reducing energy dissipation in accordance with Landauer's principle. The study covers fundamental reversible gates such as Feynman and Fredkin gates and analyzes key sequential components, including flip-flops, counters, and universal shift registers. The paper also discusses important performance parameters like quantum cost, garbage outputs, and circuit efficiency, along with their role in designing Reversible Arithmetic Logic Units (RALU) for applications in VLSI and quantum computing. Overall, the review highlights the potential of reversible logic for developing energy-efficient and scalable computing systems.

Keywords: *Reversible Logic, RALU, Quantum Cost, Garbage Outputs, Low Power VLSI, Sequential Circuits.*

1. Introduction

Reversible logic has emerged as a key technology for designing low-power and energy-efficient digital systems. In conventional irreversible logic circuits, information is lost during computation, which leads to energy dissipation in the form of heat. According to Landauer's principle, each bit of lost information results in a minimum energy loss of *kTln2*. This limitation has become a major concern in modern VLSI systems due to increasing device density and power consumption.

To overcome this issue, reversible logic circuits are introduced, where the number of inputs is equal to the number of outputs, and a one-to-one mapping exists between them. This ensures that no information is lost during computation, making reversible circuits theoretically capable of zero energy dissipation. Reversible logic plays a significant role in emerging technologies such as quantum computing, nanotechnology, and low-power CMOS design. In recent years, researchers have focused on designing efficient reversible sequential circuits such as flip-flops, counters, and shift registers. These components are essential building blocks for complex systems like Reversible Arithmetic Logic Units (RALU). The performance of reversible circuits is evaluated based on parameters such as quantum cost, garbage outputs, constant inputs, and delay, which differ from traditional metrics used in irreversible logic design.

2. Literature Review

Mummadi et al. [1], present a design focused on a universal shift-register realized with reversible logic, emphasizing minimization of quantum cost. Given the conference setting (WINTECHCON) and the title's focus on efficiency, the work likely introduces a reversible gate configuration or a new gate combination that supports bidirectional shifting, parallel load and serial-in/serial-out modes while producing fewer garbage outputs and requiring fewer constant inputs than prior designs. For a reversible RALU project, their shift-register design is directly relevant because registers are core sequential elements.**Kanchan S. Tiwari et al. [2],** signals a systematic attempt to optimize sequential reversible elements for low power by targeting quantum cost at the gate level. The paper likely surveys existing reversible gates, proposes modified or new gate primitives, and demonstrates sequential circuit implementations (latches, flip-flops, counters) with lower quantum cost and reduced garbage outputs. For your RALU, this work is valuable because it probably provides both design patterns and quantitative metrics for comparing sequential block implementations. It may also discuss synthesis methodologies or automated mapping strategies that convert desired sequential behavior into gate-level reversible realizations — information that can guide architecture-level decisions for the BDG-based ALU.**A. Aravind Kulkarni et al. [3],** concentrate on the D-flip-flop, arguably the most fundamental sequential building block. The paper likely proposes a novel reversible D-FF design tailored for quantum-VLSI compatibility, emphasizing reduced quantum cost, minimized garbage outputs, and ease of composing into larger sequential structures. For an RALU that integrates sequential

behavior (registers, pipelines), an energy-efficient reversible D-FF is pivotal; the methods used to achieve sparsity of ancilla bits or to avoid feedback-induced irreversibility will be especially useful. Their design choices — whether they prefer a particular reversible gate basis, how they handle fan-out, and how they support clocking in a reversible context — are important implementation insights for the BDG integration.

Hu Jun et al. [4], address the ALU at the architectural level with explicit orientation toward quantum processors. This work likely outlines an ALU architecture that preserves reversibility across arithmetic and logical operations, possibly describing reversible adder/subtractor modules, multiplexers, and control circuitry optimized for quantum gate cost and depth. For your project, their architectural choices—e.g., how they map multi-operand operations reversibly, how they handle status flags without destroying information, and strategies for composing arithmetic with sequential state—will be directly relevant. The paper may also evaluate resource metrics (quantum cost, depth, ancilla count) that serve as benchmarks when you claim improvements for a BDG-based RALU. **Premanand K. Kadbe et al. [5],** appear to target optimization by modifying a well-known reversible primitive (the Peres gate). Their study probably demonstrates how adaptations to the Peres gate can reduce quantum cost when constructing sequential elements (latches, FFs, counters). For designers of reversible sequential ALUs, such gate-level innovations are valuable: they suggest how classical reversible building blocks can be reworked to better support feedback/state retention with lower overhead. Examine their modified gate's truth table, decomposition into elementary quantum gates, and comparison against standard Peres-based implementations to inform BDG design trade-offs..**S. Kumari et al. [6],** focus on the JK flip-flop, which is functionally versatile and useful in finite-state machines. A reversible JK-FF design likely deals with toggling behavior while preserving input-output bijection — a nontrivial challenge because toggling can appear to "lose" previous state information. Their techniques for reversible feedback, handling of simultaneous set/reset conditions, and minimization of garbage outputs will be valuable when implementing ALU control units or state machines. Additionally, the JK-FF's applicability to counters and control logic means this design can be directly reused or modified for BDG-based sequential modules**. R. Gadelha et al. [7],** address counters — essential sequential blocks for address generation, iteration, and micro-sequencing in ALUs. Their "efficient" counters likely minimize ancilla usage and quantum cost while supporting common counting modes (binary, modulo, up/down). For an ALU with integrated sequential capability, counters are useful for microprogram counters, loop handling, or timing; thus, understanding their approach to reversible incrementation/decrementation, ripple vs. parallel structures, and concurrency control will guide the RALU's control logic design. Metrics they report (gate count, delay, garbage) will be useful comparison baselines.**T. Singh et al. [8],** introduce a shift-register design that uses a hybrid set of reversible/quantum gates to balance cost and functionality. Hybridization suggests combining different primitive gates to exploit their respective advantages (e.g., Peres for low quantum cost arithmetic, Toffoli for control). Their methodology probably includes gate decomposition strategies and layout considerations that reduce depth or ancilla overhead. For your BDG-based RALU, their hybrid approach could inspire mixed-gate implementations where BDGs are combined with other primitives to gain advantages in specific subblocks (e.g., fast shifting vs. minimal ancilla in registers). **K. R. Behera et al. [9],** review paper synthesizes existing reversible flip-flop designs, comparing them across metrics such as quantum cost, garbage outputs, constant inputs, and practical implement ability. This kind of literature survey is especially useful as a design roadmap: it identifies the state-of-the-art, common pitfalls (e.g., how feedback is handled), and open problems in flip-flop realizations. For the RALU, their taxonomy and comparative tables help justify design choices (why choose a BDG over existing gates) and provide a clear baseline against which to measure improvements in sequential elements.

3. Proposed Methodology

The proposed methodology focuses on designing an energy-efficient digital system using **reversible logic** to minimize power dissipation and information loss. The central processing unit and performs arithmetic and logical operations based on control signals. The architecture follows a modular approach in which reversible components such as **D Flip-Flop, PISO shift register, reversible counter, and universal shift register** are interconnected through a common data bus. Input data is first processed by the RALU, and the output is then transferred to different modules for storage, shifting, or sequencing operations. The **reversible D Flip-Flop** is used for data storage, while shift registers handle data movement and conversion. The universal shift register provides multiple operations such as left shift, right shift, and parallel loading. The reversible counter is used for control and sequencing purposes. All components are designed using reversible gates to ensure no information loss and low power consumption. The performance of the system is evaluated based on **quantum cost, garbage outputs, constant inputs, and delay,** with the aim of minimizing these parameters. Overall, the proposed

methodology provides a scalable and efficient solution for low-power applications in VLSI, quantum computing, and nanotechnology.

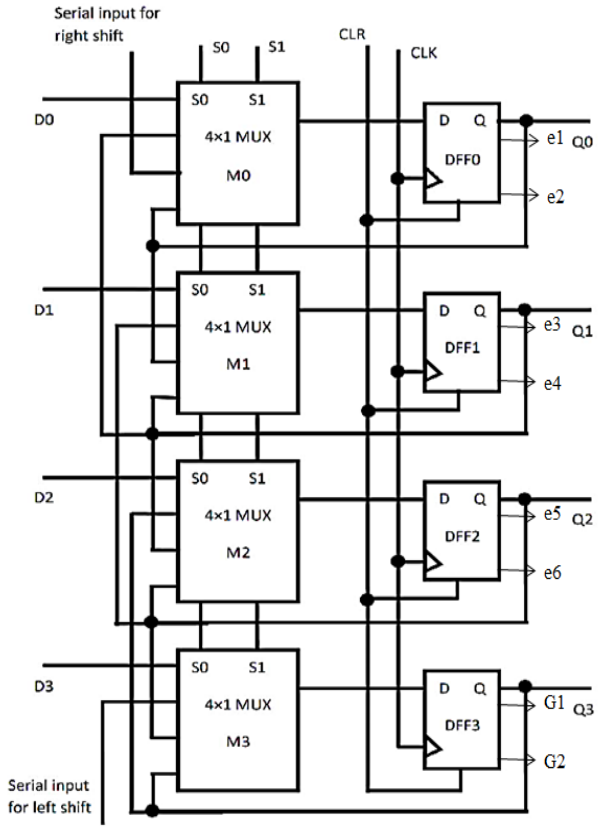

Figure 1The 4 bits basic universal shift register

4. Conclusion

This review paper highlights the significance of reversible logic in designing energy-efficient digital systems. It discusses various reversible gates and sequential components such as flip-flops, counters, and shift registers, emphasizing their role in reducing power dissipation and information loss.The study shows that optimizing parameters like quantum cost, garbage outputs, and delay can significantly improve circuit performance. Furthermore, the integration of these components in systems like Reversible Arithmetic Logic Units (RALU) demonstrates their potential in advanced applications such as quantum computing and low-power VLSI design.

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