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Wideband Six-Port Reflectometer Design using Passive Microwave Components

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ABSTRACT

The vector network analyzer (VNA) is widely used for accurate reflection coefficients measurement in microwave imaging systems. However, its high cost, bulky structure and limited portability restrict its practical applications. This paper presents the design and evaluation of a wideband six-port reflectometer operating from 1 GHz to 10 GHz as a low-cost alternative. The system is implemented using passive microwave components. Including 90° hybrid couplers, Wilkinson power dividers and correlator configurations. Three different reflectometers architecture are designed and analyzed using Advanced Design System (ADS). The performance is evaluated based on S-parameters and reflection coefficients behavior. The results show that while all configurations are functional, significant performance variants exists, particularly in impedance matching and signal balance. The study highlights the trade-off between circuit complexity and measurement accuracy, providing practical insight for reflectometer design.

Keywords: Six-port reflectometer, microwave imaging, reflection coefficient, hybrid coupler, Wilkinson power divider, wideband RF

1. INTRODUCTION

Microwave imaging is widely used applied in biomedical diagnostics, radar systems, and material characterization due to its ability to analyze dielectric properties using radio frequency signals [1]. In such systems, accurate measurement of scattering parameters, particularly the reflection coefficient, is essential. Traditionally, Vector Network Analyzers (VNAs) are used for this purpose because of their high accuracy and capability to measure both magnitude and phase of signals. However, VNAs are expensive, bulky, and primarily limited to laboratory environments, which restricts their use in portable or real-time applications [1]. To overcome these limitations, multi-port reflectometers have been developed as an alternative measurement technique. The six-port reflectometer, originally introduced as a simplified microwave measurement system, determines the complex reflection coefficient using scalar power measurements instead of direct vector analysis [1]. This significantly reduces hardware complexity and cost. Despite these advantages, achieving wideband performance and maintaining measurement accuracy remain major challenges.

Recent studies have improved reflectometer performance through enhanced calibration techniques and compact implementations [2] – [4]. However, these approaches often introduce additional system complexity. Therefore, this work focuses on designing a wideband six-port reflectometer using passive components while maintaining a balance between simplicity and performance. Three different configurations are proposed and critically evaluated to understand the impact of structural variation on measurement accuracy.

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2. BACKGROUND AND THEORY

A six-port reflectometer consists of two input ports and four output ports connected to power detectors. The system operates by measuring the power of signals resulting from the combination of incident and reflected waves. The reflection coefficient can be determined from the measured power ratios at the output ports of the multi-port reflectometer. Based on the formulation presented in [5], the complex reflection coefficient is expressed as shown in (1), where the squared magnitudes of the S-parameters represent the detected power levels at each port. This formulation enables the reconstruction of both magnitude and phase information using scalar measurements, which is the fundamental operating principle of six-port reflectometry.

$$\Gamma = \frac{(|S_{41}|)^2-(|S_{51}|)^2+j(|S_{61}|)^2-(|S_{71}|)^2}{|S_{31}|^2} \quad (1)$$

The measured power at each port is expressed as a function of linear combinations of the incident and reflected waves, influenced by the characteristics of the passive network [1]. Hybrid couplers provide equal power splitting with a 90° phase shift, while Wilkinson power dividers ensure equal amplitude distribution and impedance matching. The correlator network combines these signals to reconstruct the reflection coefficient.

Although theoretically robust, the accuracy of the six-port reflectometer is highly dependent on the precision of its components and the symmetry of the network. Any imbalance in amplitude or phase can introduce significant errors in the reconstructed reflection coefficient. This sensitivity highlights the importance of careful design and motivates the comparative analysis conducted in this study.

2.1 Comparison with Existing Works

The comparison presented in Table 1 demonstrates the progressive development of six-port reflectometer technology over the past decade, particularly in terms of bandwidth enhancement, calibration techniques, and architectural optimization. Earlier studies, such as [1] and [3], focused primarily on establishing the fundamental operation of six-port reflectometers using hybrid couplers, Wilkinson power dividers, and power detectors. These designs successfully demonstrated stable reflection coefficient measurements with relatively simple architectures and calibration methods. However, their operational bandwidths were restricted to lower frequency ranges, typically below 5 GHz, which limits their suitability for modern wideband microwave imaging and sensing applications. This limitation reflects the early stage of multi-port reflectometer development, where emphasis was placed on measurement feasibility rather than broadband capability.

The work reported in [4] represents a significant theoretical contribution by introducing a mathematical formulation for accurate reflection coefficient reconstruction in multi-port reflectometers. This formulation provides the analytical foundation for many subsequent reflectometer designs and remains relevant in current research. Nevertheless, the effectiveness of this approach is highly dependent on precise power measurements and balanced signal distribution. In practical implementations, achieving such precision is challenging due to component tolerances, insertion losses, and phase imbalance. As a result, the theoretical accuracy proposed in [4] may not always be fully realized in experimental systems.

Table 1 State-of-the-art comparison of six-port reflectometers.

Ref.	Frequency Range	Architecture	Calibration Method	Key Performance	Strength	Limitation
[1]	2–5 GHz	CRMU and Hybrid Couplers	Standard calibration	Moderate accuracy	Established architecture for microwave imaging	Narrow bandwidth
[2]	1.66–3.3 GHz	Broadband Directional Coupler and CRMU	ADS-based calibration	Good impedance matching	Compact and broadband design	Limited operating frequency
[3]	1–3 GHz	Wilkinson Power Divider and Power Detectors	Analytical calibration	Stable reflection measurement	Simple calibration structure	Low bandwidth
[4]	Wideband	Multi-Port Reflectometer (CRMU-based)	Mathematical formulation	Accurate reflection coefficient reconstruction	Established theoretical foundation	Requires precise power measurement
[5]	Broadband	Coupled-Line Directional Couplers	Accuracy analysis calibration	Improved reflectometer accuracy	Broadband coupled-line implementation	Complex coupled-line structure
[6]	2–6 GHz	CMOS Integrated Multi-Port Reflectometer	Embedded calibration	Compact RF sensing system	High integration and portability	Narrowband operation
[7]	1–5 GHz	Six-Port Microwave Biosensor	Standard calibration	High dielectric sensitivity	Biomedical sensing application	Application-specific design
[8]	Up to 10 GHz	Multi-Section Directional Couplers	Conventional calibration	Wideband response	Extended frequency coverage	Increased structural complexity
[9]	Wideband	AI-Assisted Multi-Port Reflectometer	AI-based calibration	Very high measurement accuracy	Robust against noise and errors	High computational complexity
This Work	**1–10 GHz**	Hybrid Coupler and Wilkinson Power Divider (Three Configurations)	None (ADS simulation)	Reflection coefficient approximately negative eighteen decibels	Wideband operation and multi-design comparison	Calibration not implemented

Broadband improvement efforts can be observed in [2] and [5], where directional couplers and coupled-line structures were introduced to extend operational frequency ranges. The use of broadband couplers improved impedance matching and enhanced frequency response, demonstrating that component selection plays a critical role in wideband reflectometer performance. However, these approaches also increased structural complexity, particularly in coupled-line implementations, which are more difficult to fabricate and optimize. This indicates an important trade-off between bandwidth extension and implementation practicality. Although broadband performance was improved, maintaining consistent phase and amplitude balance across the entire frequency range remained a significant challenge.
Recent works from 2023 onwards, including [6], [7], [8], and [9], demonstrate a shift toward advanced integration and intelligent calibration methods. The CMOS-integrated reflectometer in [6] highlights the growing demand for compact and portable RF sensing systems. While high integration improves portability and reduces physical size, the operational bandwidth remains relatively limited. Similarly, the biosensor application in [7] demonstrates the adaptability of six-port reflectometers for biomedical sensing, but the design is highly application-specific and may not be easily generalized for other RF measurement systems.

The introduction of multi-section directional couplers in [8] successfully extends frequency operation up to 10 GHz, which aligns more closely with the requirements of modern wideband systems. However, the increased structural complexity introduces additional design challenges, including impedance control, phase consistency, and fabrication sensitivity. Furthermore, the AI-assisted calibration approach proposed in [9] demonstrates substantial improvements in measurement accuracy and robustness against noise. Although artificial intelligence techniques can compensate for hardware imperfections and nonlinearities, they significantly increase computational complexity and require large datasets for training and optimization. Consequently, the system becomes more dependent on software processing rather than intrinsic hardware performance.

In comparison with these studies, the proposed work adopts a different design philosophy by emphasizing hardware simplicity while still achieving wideband operation from 1 GHz to 10 GHz. Instead of relying on advanced calibration or artificial intelligence techniques, the proposed reflectometer focuses on optimizing passive microwave components through three different configurations. This comparative approach provides a deeper understanding of the relationship between architecture and performance, which is not commonly explored in previous works. The fully symmetric configuration demonstrates that maintaining phase balance through hybrid couplers significantly improves impedance matching and signal stability. Meanwhile, the hybrid and simplified configurations illustrate how reducing component complexity affects phase coherence and measurement reliability.

Despite achieving wideband performance, the absence of calibration remains a major limitation of the proposed work. Without calibration, systematic errors caused by component imperfections and fabrication tolerances cannot be fully compensated. Therefore, although the simulation results demonstrate acceptable reflection coefficient performance, the practical accuracy of the system may be limited in real-world applications. This suggests that future reflectometer development should aim to achieve a balance between hardware simplicity, bandwidth performance, and calibration efficiency rather than focusing exclusively on any single aspect.

Overall, the comparison highlights a clear evolution from simple narrowband reflectometers toward intelligent and highly integrated systems. However, it also reveals that improvements in bandwidth and accuracy are frequently accompanied by increased structural or computational complexity. The proposed work contributes to this progression by demonstrating that competitive wideband performance can still be achieved using passive microwave architectures, provided that sufficient attention is given to phase balance and signal distribution within the correlator network.

3. METHODOLOGY

The circuit schematic of the proposed reflectometer is designed using passive microwave components was arranged in three different configurations as illustrated in Figure 1. The design and simulation are carried out using Advanced Design System (ADS), which enables detailed S-parameter analysis. The three distinct configurations of the proposed six-port reflectometer, namely the fully symmetric, hybrid, and simplified designs as illustrated in Figure 1 (a), (b) and (c), respectively. Each configuration demonstrates a different approach to signal distribution and correlation, particularly in the use and placement of hybrid couplers and Wilkinson power dividers, which significantly influence the overall system performance.

In the fully symmetric design, all signal paths are constructed using hybrid couplers, resulting in a balanced and uniform architecture. This configuration ensures that both amplitude and phase of the signals are evenly distributed throughout the network. Such symmetry is essential in six-port reflectometry, as accurate reconstruction of the reflection coefficient depends heavily on maintaining consistent phase relationships between signals. The absence of power dividers in this design minimizes amplitude imbalance and reduces the likelihood of signal distortion. Consequently, this structure is expected to provide the highest measurement accuracy and stability, although it inherently requires a higher number of components, leading to increased circuit complexity and size.

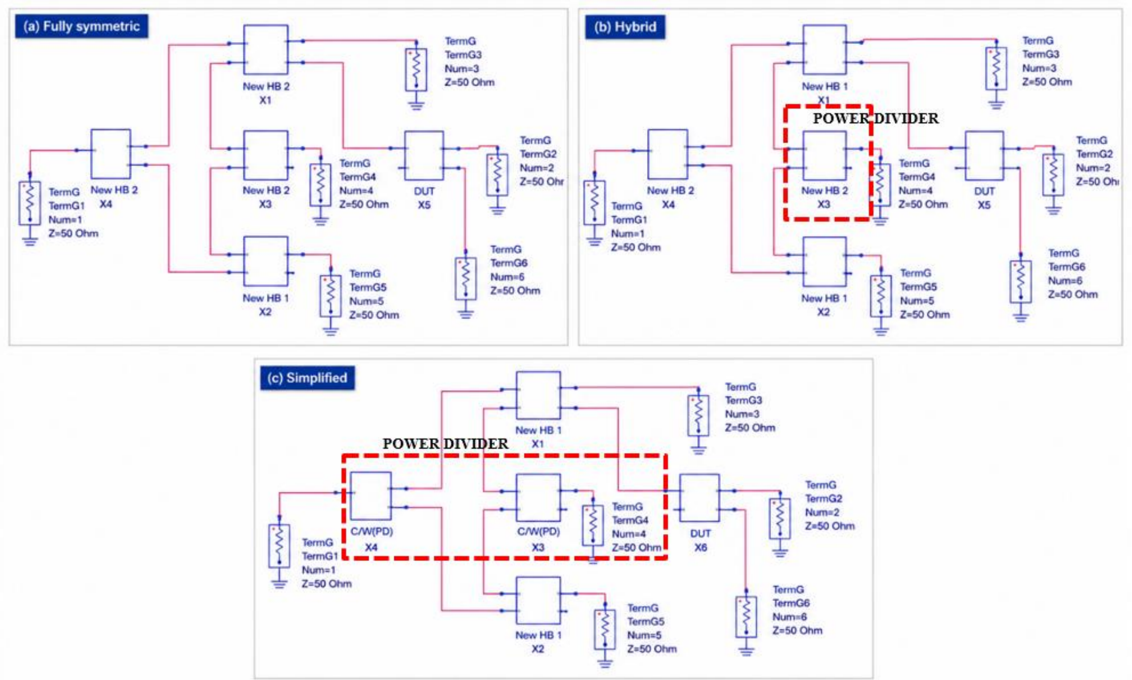

Figure 1. Circuit schematics of the proposed six-port reflectometer designs: (a) fully symmetric, (b) hybrid, and (c) simplified.

In contrast, the hybrid design introduces a Wilkinson power divider within the correlator network, as highlighted in the Figure (b). The inclusion of the power divider modifies the signal flow by splitting the input signal into equal amplitude components without introducing a phase shift, unlike hybrid couplers. While this reduces the number of hybrid couplers required and simplifies the circuit, it also introduces asymmetry in the signal paths. This asymmetry can lead to phase imbalance and reduced isolation between ports, which may degrade the accuracy of the reflection coefficient measurement. However, the hybrid configuration represents a compromise between performance and complexity, offering a more practical implementation with moderate accuracy.

The simplified design as in Figure 1 (c) was further extends this approach by incorporating multiple power dividers, significantly reducing the reliance on hybrid couplers. As shown in the figure, the signal routing becomes less uniform, with several paths dominated by amplitude-only splitting rather than phase-controlled distribution. This results in a loss of phase coherence across the network, which is critical for precise reflectometry. Although this configuration offers advantages in terms of reduced component count, lower cost, and compactness, the degradation in signal integrity is more pronounced. The increased use of power dividers leads to weaker control over phase relationships, making the system more susceptible to measurement errors and frequency-dependent variations.

A key observation from these configurations is that the role of the hybrid coupler is fundamental in preserving phase information, while the Wilkinson power divider primarily supports amplitude distribution. Replacing couplers with power dividers simplifies the circuit but compromises the ability of the system to accurately reconstruct the reflection coefficient. Therefore, a balance must be achieved between structural simplicity and measurement reliability. The fully symmetric design prioritizes accuracy, the hybrid design offers a balanced trade-off, and the simplified design emphasizes cost and compactness at the expense of performance. The summary of the comparison of proposed six-port reflectometer configuration highlights in Table 2, was shows the impact of circuit architecture on the performance of the six-port reflectometer.

Table 2 Comparison of proposed six-port reflectometer configuration.

Design	Architecture	Key Components	Signal Characteristics	Advantages	Limitation
(a)	Fully symmetric	Four hybrid couplers	Strong phase balance, good isolation, stable amplitude distribution. $S_{11} \approx -18$ dB	High accuracy, best impedance matching, strong isolation, stable performance across frequency	Higher complexity, larger size, increased component count
(b)	Hybrid (Mixed structure)	Three hybrid couplers and a Wilkinson power divider	Moderate phase balance, acceptable signal distribution. $S_{11} \approx -6.7$ dB	Reduced complexity, balanced trade-off between performance and cost	Degraded matching, phase imbalance due to asymmetry
(c)	Simplified	Two hybrid couplers and two Wilkinson power dividers	Weaker phase control, less stable amplitude distribution. $S_{11} \approx -8.69$ dB	Lowest complexity, compact design, reduced cost	Poor impedance matching, higher signal fluctuation, reduced measurement accuracy

Overall, the methodology highlights how the arrangement and selection of passive components directly influence the operational characteristics of the six-port reflectometer. The comparative analysis of these three configurations provides valuable insight into the design trade-offs, particularly the impact of phase balance, signal symmetry, and component reduction on system performance.

4. RESULTS AND DISCUSSION

The results obtained as shown in Figure 2 represents the three proposed six-port reflectometer configurations, respectively. The results reveal important insights into the relationship between circuit architecture and measurement performance, particularly when interpreted through the theoretical framework of multi-port reflectometry. The analysis clearly demonstrates that structural symmetry and phase control are the dominant factors governing system accuracy, rather than merely the number of components or simplicity of implementation.

The results in Figure 2(a) shows the fully symmetric configuration exhibits the best performance, which is consistent with the theoretical requirement that both amplitude and phase information must be preserved for accurate reconstruction of the reflection coefficient, Γ as defined in (1) [4]. The use of four hybrid couplers ensures that equal power splitting is accompanied by precise 90° phase shifts, allowing the correlator network to maintain coherent signal relationships across all ports. This results in improved impedance matching, S_{11} is approximately −18 dB and strong isolation, indicating minimal internal interference. From a theoretical standpoint, this configuration most closely approximates the ideal six-port model, where balanced signal paths enable accurate power-based reconstruction of complex reflection coefficients.

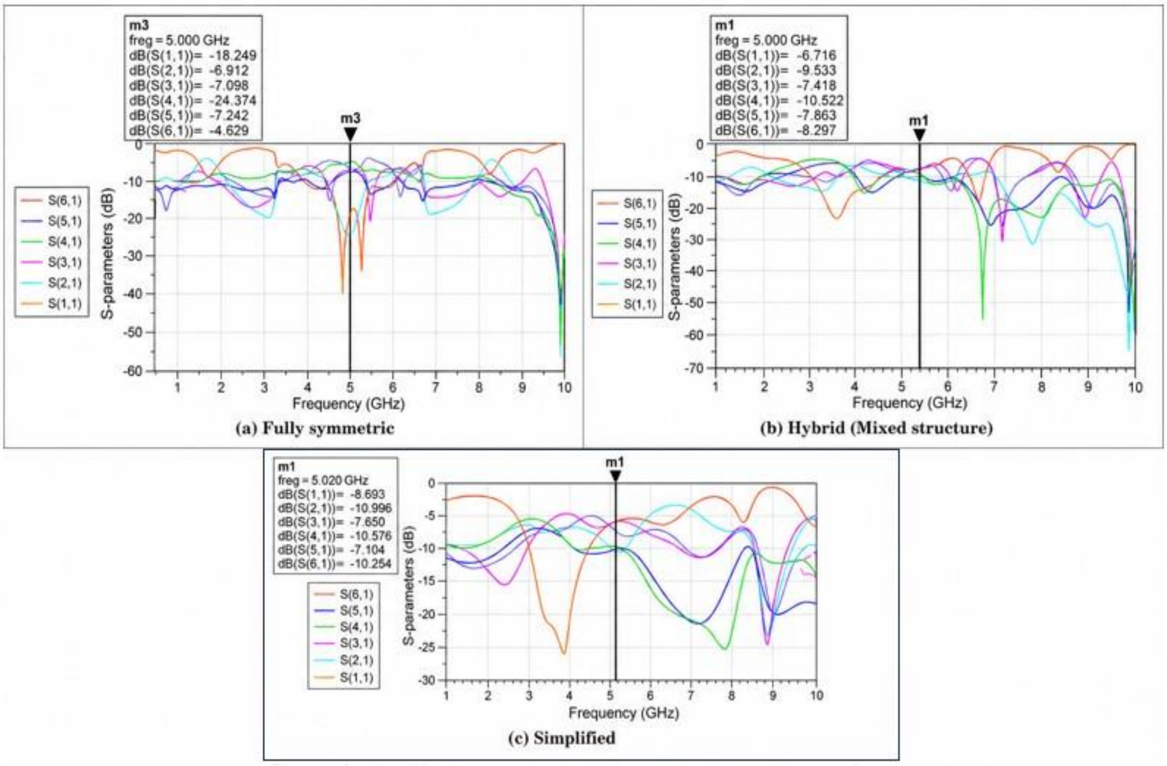

Figure 2. Simulated S-parameter response of the proposed six-port reflectometer designs: (a) fully symmetric, (b) hybrid, and (c) simplified.

However, while the fully symmetric design provides superior performance, it also introduces practical limitations. The increased number of hybrid couplers leads to higher insertion loss, larger physical size, and increased fabrication complexity. In real-world implementations, these factors may offset the theoretical advantages, particularly in applications requiring compact and low-cost systems. Therefore, although the design is optimal from a theoretical perspective, its practicality must be evaluated in the context of system constraints.

The hybrid (mixed) configuration represents an attempt to balance performance and complexity by replacing one hybrid coupler with a Wilkinson power divider. While this reduces component count and simplifies the circuit, the results indicate a noticeable degradation in impedance matching, S_{11} is approximately -6.7 dB. This behaviour can be explained by the absence of phase shifting in the power divider, which disrupts the phase balance required by the six-port theory. As a result, the correlator network becomes less effective in reconstructing the reflection coefficient, leading to reduced accuracy. This highlights a critical limitation: even partial substitution of phase-sensitive components can significantly impact system performance. The simplified configuration further reduces complexity by incorporating multiple power dividers, but this comes at the cost of substantial performance degradation. The results show increased fluctuation in S-parameters and weaker impedance matching, S_{11} is approximately −8.69 dB, particularly across the higher frequency range. Theoretically, this is expected because power dividers only preserve amplitude information and do not contribute to phase control. Since equation (1) relies on precise power differences derived from coherent signal combinations, any loss of phase integrity directly affects the accuracy of Γ. Consequently, the simplified design fails to maintain the necessary signal conditions for reliable reflectometry, making it less suitable for high-precision applications.

Another observation is the frequency-dependent behaviour across all configurations. While acceptable performance is achieved around the central frequency, where approximately at 5 GHz, deviations become more pronounced at higher frequencies, which above 8 GHz. This can be attributed to non-ideal effects in microstrip implementations, including dispersion, parasitic coupling, and impedance mismatch. These effects introduce additional phase and amplitude errors, which are not accounted for in the ideal theoretical model. This discrepancy between theory and practical implementation highlights the importance of considering real-world limitations in wideband reflectometer design. Furthermore, the absence of calibration in all three configurations represents a significant limitation. While the theoretical formulation in [4] enables reflection coefficient reconstruction from power measurements, practical systems require calibration to compensate for component imperfections and systematic errors. Without calibration, the measured S-parameters may not accurately represent the true reflection behaviour of the DUT. Therefore, although the proposed designs demonstrate functional operation, their measurement accuracy remains inherently limited.

In comparison with state-of-the-art approaches, which often incorporate advanced calibration techniques or AI-based correction methods, the proposed work prioritizes hardware simplicity over computational complexity. While this reduces implementation cost, it also places greater reliance on the intrinsic accuracy of the circuit design. This trade-off underscores a fundamental challenge in reflectometer development: achieving high accuracy without significantly increasing system complexity. Overall, the critical analysis confirms that the fully symmetric design offers the best alignment with theoretical expectations, while the hybrid and simplified designs illustrate the consequences of reduced phase control and structural imbalance. The findings emphasize that maintaining phase coherence is essential for accurate multi-port reflectometry and that design simplification must be carefully managed to avoid compromising performance.

5. CONCLUSION

This paper presents the design and critical evaluation of a wideband six-port reflectometer using passive microwave components for reflection coefficient measurement. Three configurations, namely the fully symmetric, hybrid, and simplified designs, are developed and analyzed to investigate the influence of circuit architecture on system performance. The results demonstrate that the fully symmetric design provides the best performance, achieving good impedance matching, where the reflection coefficient is approximately negative eighteen decibels, along with strong isolation due to balanced amplitude and phase distribution. In contrast, the hybrid and simplified configurations show degraded performance because of reduced phase control and structural asymmetry. This finding highlights the importance of maintaining signal coherence in multi-port reflectometer design. The analysis further confirms that reducing circuit complexity may lower implementation cost, but it also introduces limitations in measurement accuracy and stability. The study also demonstrates that wideband operation from 1 gigahertz to 10 gigahertz can be achieved using a passive architecture without relying on complex calibration or advanced computational techniques. However, the absence of calibration remains a limitation that may affect accuracy in practical applications. Overall, the proposed reflectometer provides a viable low-cost alternative to conventional vector network analyzers while offering valuable insights into the trade-offs between complexity, performance, and reliability. Future work should focus on incorporating calibration techniques and experimental validation to improve accuracy and support real-world implementation.

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