Stream Processing Architectures for Real-Time Internet of Things Data

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Article Information	ABSTRACT
	This study provides a comprehensive comparative review of stream processing architectures for real-time Internet of Things (IoT) data, with particular emphasis on their applicability to Indonesia's growing digital ecosystem. Three dominant models—Lambda, Kappa, and Edge Processing—were systematically analyzed based on performance metrics such as latency, scalability, and fault tolerance. The research integrates qualitative literature review and quantitative benchmarking using established frameworks, including Apache Kafka, Spark Streaming, and Apache Flink. Results indicate that the Lambda Architecture demonstrates the highest accuracy and resilience but involves complex deployment, while the Kappa Architecture offers simplified scalability through a continuous streaming paradigm. Edge Processing achieves the lowest latency but presents security and data integrity challenges. Considering Indonesia's diverse network infrastructure, a hybrid edge-cloud model emerges as the most effective architecture for national IoT implementation. This approach combines real-time responsiveness with centralized reliability, making it well-suited for critical domains such as transportation, healthcare, and smart cities. Future research should focus on large-scale pilot testing of hybrid architectures, including AI-based anomaly detection and security protocols, to enhance operational reliability and ensure sustainable IoT deployment. **Keywords**: IoT; Stream Processing; Real-Time Data; Edge Computing; Lambda Architecture; Kappa Architecture

1. Introduction

The Internet of Things (IoT) has fundamentally established itself as a cornerstone of the digital revolution, enabling the interconnectivity and real-time communication

of millions of devices. This connectivity facilitates the continuous collection of extensive and varied data. Real-time data processing, or stream processing, is thus critically important for the rapid analysis and quick response to this continuous data influx, particularly across vital sectors such as industry, transportation, healthcare, and smart cities. This capability ensures that decision-making is prompt, significantly enhancing both operational efficiency and effectiveness [1-3].

The Challenge of Data Velocity and Volume

The primary challenges inherent in IoT data processing are the immense volume of data, the extremely high-velocity of the data flow, and the significant heterogeneity originating from diverse sensors and devices. Traditional batch processing architectures are increasingly insufficient for this task due to their high latency and lack of responsiveness to real-time application demands. Consequently, much research and industry adoption have shifted towards stream processing architectures. These modern frameworks are typically event-driven and based on microservices, offering superior flexibility, scalability, and enhanced response speed [4, 6].

Architectural Models and Considerations

A variety of stream processing architectural models have been developed. These include the Lambda Architecture, which merges batch and real-time processing to optimize both accuracy and speed, and the Kappa Architecture, which simplifies processing by relying exclusively on data streaming. Each of these models presents specific advantages and drawbacks tailored to application needs, requiring careful consideration of processing speed, management complexity, and scalability potential [7, 6, 8].

National Context and Research Focus

Within the context of Indonesia, the necessity for robust, real-time IoT data processing systems is becoming more urgent. This urgency aligns with the substantial year-over-year growth in IoT technology adoption. Data from the Central Statistics Agency (BPS) indicates a significant surge in IoT deployment within the agriculture, health, and transportation sectors, all of which require real-time data analysis for strategic and operational decision-making [9, 10].

This research, therefore, aims to conduct an in-depth examination of the stream processing architectures currently utilized for real-time IoT data processing. It will evaluate their strengths and limitations, and assess their relevance and adaptability at a national scale. This assessment will be informed by real-world data and validated requirements from official institutions such as BPS and the Ministry of Communication and Information Technology (Kominfo). This approach is expected to culminate in specific architectural recommendations optimized for enhancing the IoT ecosystem throughout Indonesia [11, 12].

2. Materials and Method

This study adopts a comprehensive literature review and comparative analysis approach to examine real-time data processing architectures for the Internet of Things (IoT). The foundation of this investigation is built on reputable academic and technical sources widely recognized in the domains of big data systems and IoT. Supporting data, including statistics and real-time data requirements specific to Indonesia, were obtained from the Central Statistics Agency (BPS), the Ministry of Communication and Informatics (Kementerian Kominfo RI), and the State Cyber and Crypto Agency (Lembaga Sandi Negara), ensuring both the validity and local relevance of the findings [9, 10].

The research methodology combines qualitative and quantitative elements. The qualitative component involves an in-depth comparative analysis of several stream processing architectures, including the Lambda Architecture, Kappa Architecture, and Edge Computing. Key performance indicators for comparison—such as latency, scalability, fault tolerance, heterogeneous data integration, and resource efficiency— were evaluated systematically. The comparison process was guided by an assessment criteria table developed to ensure consistency and transparency across all evaluated architectures [12, 13].

The quantitative component employs benchmark data derived from leading stream processing platforms, including Apache Kafka, Apache Flink, and Spark Streaming. The evaluated metrics include end-to-end latency, processing throughput, and system resilience under partial failure conditions. All benchmarking procedures adhere strictly to the latest technical standards and methodologies available in the literature, allowing replication by other researchers [12, 14].

This research does not involve in-situ experiments or human and animal subjects; therefore, ethical approval was not required. All protocols, data, and code used in this study will be made publicly accessible to support transparency and replicability throughout the review and publication process [15, 16].

3. Result

Characteristics of IoT Data and Processing Requirements

IoT data is characterized by its continuous flow and massive scale, qualifying it as big data that demands rapid and efficient processing capabilities. The constant movement of information from environmental sensors, wearable technologies, and transportation systems often reaches volumes of terabytes per hour. According to statistical reports from the Central Statistics Agency (BPS, 2024), IoT penetration in Indonesia has grown by approximately 35% annually, underscoring the increasing need for real-time monitoring, particularly in the agricultural and healthcare sectors.

Key Stream Processing Architectures

The analysis focused on the following principal architectures:

Lambda Architecture: This model employs two distinct pipelines a batch layer and a speed layer to achieve a balance between high data accuracy and low processing latency. Nevertheless, the inherent complexity involved in its implementation often poses a significant challenge.

Kappa Architecture: By exclusively focusing on the stream processing paradigm and eliminating the need for a separate batch layer, this architecture offers a simplified system structure. Its effectiveness, however, is contingent upon robust log storage technologies, such as Apache Kafka.

Edge Stream Processing: This approach involves offloading a portion of the processing workload to the edge devices themselves, effectively minimizing network load and reducing end to end latency.

Implementation Case Studies

The research determined that an integrated Edge and Cloud architecture provides the highest degree of flexibility for Indonesia's national IoT landscape, especially given the challenges posed by uneven network infrastructure distribution. In the transportation domain, leveraging the Kappa Architecture alongside the Spark

Streaming platform yielded impressive performance metrics, including an average latency of 50 ms combined with high throughput. Conversely, for critical security systems within healthcare IoT, a combined Lambda Architecture with real-time encryption capabilities is recommended.

Table 1. Presents a Comparative Performance Overview of The Analyzed Architectures Across Specific Iot Domains.

Architecture	Latency (ms)	Scalability	Case Usage
Lambda	70	High	Security systems & Auditing
Kappa	50	Very High	Transportation and log data
Edge Processing	30	Medium	Environmental & health monitoring

Data Validation and Reliability

The reliance on data published by BPS ensures that the documented real-time needs and data volumes accurately reflect the operational reality within the Indonesian context [9]. Specifically, a dedicated study using Jakarta transportation data confirmed the capability of the analyzed stream processing architectures to perform valid data analysis that aligns precisely with existing vehicle statistics [14].

4. **Discussion**

Architectural Trade-offs in Real-Time IoT

The analysis confirms the inherent complexity in selecting an appropriate stream processing architecture for real-time Internet of Things (IoT) systems. No single framework can effectively address all application needs. The architectural decision must therefore consider application characteristics, data volume, and available infrastructure capacity.

The Lambda Architecture offers strong advantages in data accuracy and fault tolerance through parallel batch and streaming processes. This dual-layer approach supports error correction and maintains data consistency, even during component failures. However, its complexity in design and maintenance often limits deployment in resource-constrained environments because it requires managing and synchronizing two distinct processing models.

In contrast, the Kappa Architecture simplifies the system by employing a continuous streaming pipeline, providing better scalability and easier maintenance. It is highly effective for applications that demand rapid processing and frequent data updates. Its reliance on dependable log storage ensures data consistency and enables reprocessing when necessary. Previous studies have demonstrated its effectiveness in telecommunications and e-commerce sectors, where massive data volumes make batch validation impractical [12, 14].

The Evolution to Edge Processing and Emerging Technology

The transition toward edge stream processing marks a major step forward in real-time IoT architecture. It addresses two critical challenges: network latency and overreliance on centralized cloud systems. By processing data closer to its source, edge computing reduces transmission delays and improves responsiveness. Nevertheless, this approach introduces new security challenges, especially regarding data integrity, confidentiality, and availability in distributed environments. Advanced cryptographic protocols and real-time synchronization between edge and cloud layers are essential to safeguard information and ensure operational continuity.

Emerging technologies such as 5G and Artificial Intelligence (AI) are reshaping IoT stream processing architectures. The high bandwidth and ultra-low latency of 5G enable faster data transfer, while AI enhances automation, predictive analytics, and adaptive decision-making at both edge and cloud levels. Integrating AI into stream processing allows dynamic adaptation to data patterns, optimized resource allocation, and improved system efficiency. Studies have shown that 5G–AI integration can significantly enhance predictive maintenance, anomaly detection, and operational reliability across industries [17–19].

Local Context and Future Directions

Within the Indonesian context, characterized by uneven technological infrastructure distribution and significant regional variation in IoT requirements, the integration of a hybrid edge-cloud architecture becomes essential. This approach not only improves processing speed and responsiveness but also enables the extension of IoT services into areas with limited connectivity. This research underscores the importance of developing an inclusive and sustainable IoT ecosystem model that

recognizes the advantages of hybrid technology and adapts them to specific local conditions.

Despite these insights, a primary limitation of this study is the scarcity of comprehensive actual experimental data from diverse field applications, which is critical for validating the performance and security of the proposed stream processing solutions. Therefore, follow-up research is highly recommended to conduct systematic, direct testing at a national pilot scale, including rigorous evaluation of security protocols, architectural optimization, and measurement of implementation impact on business and social performance

In conclusion, the findings of this research offer a significant contribution to both the scientific and practical understanding of IoT stream processing architectural strategies. It opens new perspectives for the development of adaptive and secure technologies that will underpin the global digitalization era.

5. Conclusions

This study concludes that stream processing architectures are fundamentally indispensable for the real-time processing of data generated by the Internet of Things (IoT). The findings confirm that each architectural model possesses distinct strengths and limitations, requiring that the selection process be carefully aligned with specific application requirements, infrastructure characteristics, and the nature of the managed data flow. Models such as the Lambda Architecture offer high data accuracy and strong fault tolerance but involve greater implementation complexity. In contrast, the Kappa Architecture simplifies system management through a single continuous streaming pipeline, enhancing scalability and adaptability across multiple application domains. Considering Indonesia's diverse infrastructure landscape, the integration of a hybrid model that combines edge and cloud computing emerges as the most effective strategy to fulfill real-time demands while mitigating challenges related to network variability and device capabilities.

The primary limitation of this research lies in the limited availability of large-scale, real-world experimental data needed to validate the performance, security, and reliability of the proposed architectures. Therefore, future studies should focus on conducting national-level pilot projects to empirically assess system performance under real operational conditions. These initiatives should include the testing of security protocols, optimization of architectural configurations, and evaluation of

system resilience against fluctuating data loads and network constraints. Such efforts will ensure that Indonesia's digitalization and IoT implementation strategies are grounded in empirical evidence. In conclusion, this work provides a scientific foundation for the development of adaptive, scalable, and secure IoT stream processing systems and highlights the need for further research to enhance their sustainability and responsiveness in a rapidly evolving global IoT ecosystem.

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