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IIoT Network Analysis: Age of Information and Reliability Trade-offs

1. Introduction

The Age of Information (AoI) is a critical metric in the Industrial Internet of Things (IIoT) that represents the freshness of data received from remote sensors and devices. Unlike traditional latency measures, AoI captures the elapsed time since the last received update, making it a more meaningful measure for applications that depend on timely data.

In this project, we explore the trade-off between AoI and reliability (measured as Packet Loss Probability or PLP) using a simulated dataset inspired by the research paper: Farag, H., Ali, S. M., & Stefanović, Č. (2023). *On the Analysis of AoI-Reliability Tradeoff in Heterogeneous IIoT Networks*. Our objective is to analyze the patterns in IIoT network parameters, develop machine learning models to predict AoI, and propose practical strategies for optimizing IIoT performance.

2. Conceptual Understanding

AoI is vital in IIoT applications where the timing of updates influences decision-making, such as predictive maintenance or emergency alerts. For instance, in a smart factory, outdated sensor data might result in equipment overheating before an operator is alerted.

There are two main traffic types in IIoT:

* AoI-oriented traffic prioritizes the freshness of updates (e.g., real-time temperature sensors).
* Deadline-oriented traffic focuses on meeting specific timing deadlines (e.g., sending a shutdown signal within 100ms).

Understanding these differences is key to designing network protocols that optimize both performance and reliability.

3. Data Exploration and Key Findings

We examined the dataset iiot\_network\_data.csv, which includes variables like transmission probability, network load, traffic type, age of information, and packet loss. Key insights from data visualization and analysis include:

1. Higher transmission probability is associated with lower AoI, suggesting that reliable delivery improves freshness.
2. Deadline-oriented traffic exhibits higher variance in AoI, indicating potential timing inefficiencies.
3. Strong correlations were observed between packet loss and both AoI and network load, highlighting their interdependence.

Visual tools such as scatter plots, box plots, and heatmaps helped reveal these patterns.

4. Machine Learning Analysis

We trained a Random Forest Regressor to predict AoI based on network parameters. The model achieved strong performance:

* Mean Squared Error (MSE): Low
* R-squared Score: High

The most important features influencing AoI were:

* Transmission Probability
* Packet Loss
* Network Load

We also tested the model on new hypothetical configurations and found the predictions to align with theoretical expectations: higher transmission reliability leads to lower AoI.

As a bonus, a deep learning model (using TensorFlow) was developed to predict AoI and PLP simultaneously. While it showed comparable performance, the Random Forest model was more interpretable and efficient for this use case.

5. Insights and Recommendations

Key Factors Impacting AoI-PLP Trade-off:

* Higher packet loss increases AoI.
* Network congestion (high load) reduces both reliability and freshness.

Strategies to Optimize IIoT Performance:

1. Dynamic Update Scheduling: Prioritize updates from critical sensors when AoI thresholds are exceeded.
2. Adaptive Routing: Use multi-path routing to reduce packet loss during peak loads.

Real-World Applications:

* Smart Grid Monitoring: Accurate and timely data from meters improves power distribution decisions.
* Autonomous Manufacturing: Ensures robots respond to the most recent environmental inputs.

6. Conclusion

Understanding the AoI and PLP trade-off enables engineers to design IIoT networks that are both reliable and responsive. By combining data-driven techniques with insights from research, we can better optimize system performance, prevent failures, and enhance safety across industrial domains.

References

* Farag, H., Ali, S. M., & Stefanović, Č. (2023). *On the Analysis of AoI-Reliability Tradeoff in Heterogeneous IIoT Networks*. arXiv preprint arXiv:2311.13336.
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