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ITAI 3377- AI at the Edge and IIOT Environments

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March 25, 2025.

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

1. Conceptual Understanding:

Age of Information (AoI) and Its Importance in Ilott: Age of Information (AoI) measures how fresh the received data is, indicating the time since the last update was generated. Unlike delay or throughput, AoI directly reflects data timelines crucial for real-time decision-making in IIoT systems. In industrial settings, outdated data can lead to poor decisions, product defects, or safety risks.

For example, if temperature sensors in a smart factory provide stale data, the system may fail to trigger cooling in time, causing equipment damage. Low AoI ensures timely, accurate responses based on the most current sensor data.

AoI-oriented vs. Deadline-oriented Traffic in IIoT: In IIoT networks, AoI-oriented traffic prioritizes data freshness through frequent, periodic updates (e.g., sensor readings) to ensure the system acts on the latest information.

Example of Aol-oriented traffic: A vibration sensor sends updates every second to detect anomalies in real time.

Deadline-oriented traffic focuses on delivering critical messages within strict time limits, where reliability outweighs freshness.

Example of Deadline-oriented traffic: A gas leak detector must send an alert immediately, delays could lead to serious hazards.

These traffic types compete for network resources, requiring careful balance to optimize both data freshness and timely delivery.

2. Data Exploration & Key Patterns

- High transmission probability is associated with lower AoI, meaning that frequent data updates help maintain information freshness at the receiver.
- High packet loss probability (PLP) and poor channel quality result in higher AoI, indicating that unreliable network conditions lead to delayed or missed updates, reducing data freshness.
- Traffic type plays a significant role in AoI performance. AoI-oriented traffic consistently achieves lower and more stable AoI values compared to deadline-oriented traffic, which shows more variability.
- The presence of extreme AoI values, including infinite values, suggests possible network failures or severe congestion under certain conditions.
- Correlation analysis supports these trends, showing that AoI decreases as transmission probability increases, and PLP decreases as channel quality improves.

3. Random Forest Model – AoI Prediction

Performance:

- **MSE:** 427,449

- **R^2 Score:** 0.806

  The model captures over 80% of the variance in AoI—strong performance.

Feature Importances:

Feature	Importance
packet_loss_probability	Highest
transmission_probability	High
channel_quality	Moderate
capture_threshold	Low
num_nodes	Low

Insight: Packet loss and transmission probability are the strongest drivers of AoI. More packet loss means older data. I included packet_loss_probability in the input data for model training because the model did not perform well. MSE (AoI) was over 3,423,000 which was too high and R2 was very poor at a negative 0.55.

4. Hypothetical Scenario Predictions

Predicted AoI for different configurations showed:

- Best performance when PLP is low, and channel quality is high.
- Even high transmission probability can't compensate for poor reliability.

The model generalizes well to realistic configurations.

5. Insights & Recommendations

a) Key AoI–PLP Trade-off Factors

- Higher transmission frequency reduces AoI but can increase PLP if the network is congested.
- Channel quality and packet loss are critical for both data freshness and reliability.

b) Optimization Strategies

- **Adaptive Transmission Control**: Adjust transmission rates based on congestion.
- **Channel-aware Scheduling**: Favor nodes with good link quality.
- **Traffic Prioritization**: Allocate resources based on traffic criticality.
- **Topology Management**: Reduce node density and improve routing efficiency.

c) Real-World Applications

- **Smart Factories**: Low AoI enables real-time fault detection.
- **Power Grids**: Timely data prevents blackouts.
- **Autonomous Logistics**: Reliable updates support safe robot movement.
- **Disaster Monitoring**: Emergency alerts must be timely and fresh.

This project demonstrates the importance of feature selection, interpretability, and modeling trade-offs in IIoT systems. By combining visual analytics with classical and deep learning approaches, I gained deep insights into how network conditions influence data freshness and reliability, supporting better design decisions in real-world IIoT deployments.

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. https://arxiv.org/abs/2311.13336

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