Oren Moreno

ITAI 3377

March 25, 2025

Professor Patricia McManus

L07 IIoT Network Analysis: Age of Information and Reliability Trade-offs

**Introduction**

This report summarizes the analysis of Age of Information (AoI) and reliability metrics in Industrial Internet of Things (IIoT) networks. The study investigates the relationship between data freshness and reliability in networks that support both AoI-oriented and deadline-oriented traffic.

**Conceptual Understanding**

Age of Information (AoI) measures how fresh data is at a receiver, defined as the time elapsed since the most recently received packet was generated. Unlike traditional metrics like delay that focus on single packet transit time, AoI captures information timeliness from the destination's perspective. In IIoT applications like smart manufacturing, AoI is vital because outdated data can lead to inefficiencies or failures in dynamic environments.

IIoT networks support two distinct traffic types. AoI-oriented traffic involves regular, time-triggered updates aimed at keeping the controller's information fresh. For example, a pressure sensor in a chemical plant sends periodic updates to maintain low AoI, ensuring the controller has the latest readings for real-time adjustments. Conversely, deadline-oriented traffic is event-triggered and sporadic, delivering critical data that must reach the controller within strict time limits. An example would be an emergency alarm in an industrial assembly line that must be delivered promptly to halt operations and prevent damage.

**Data Exploration**

The scatter plot of transmission probability versus age of information reveals that higher transmission probabilities generally correlate with lower AoI values, but with diminishing returns. This suggests that increasing transmission probability beyond a certain point may not significantly improve information freshness. The visualization also indicates variation between traffic types in their AoI distribution patterns.

A graph of a number of blue and orange dots

AI-generated content may be incorrect.

The box plot comparing AoI by traffic type demonstrates differences in AoI distributions between deadline-oriented and AoI-oriented traffic. Deadline-oriented traffic shows more variability and appears to be slightly more right-skewed in AoI values, aligning with its sporadic nature compared to the more consistent AoI-oriented traffic. Both traffic types exhibit outliers with extremely high AoI values.

A graph of a graph showing a number of traffic type

AI-generated content may be incorrect.

The correlation heatmap reveals important relationships between network parameters. A strong positive correlation (0.54) exists between the number of nodes and packet loss probability, indicating that increased network congestion from more nodes leads to higher packet loss. A negative correlation (-0.45) between channel quality and packet loss probability confirms that better channel quality reduces packet loss. Interestingly, transmission probability has only a weak negative correlation (-0.06) with age of information, suggesting other factors like network congestion and interference might play more significant roles in determining AoI.

A diagram of a heat map

AI-generated content may be incorrect.

**Machine Learning Model Development**

Initial model performance was poor, with a test R-squared of -0.54, indicating the model performed worse than a simple mean predictor. After filtering extreme outliers (top 1% of AoI values), performance improved significantly. The training MSE decreased from 380,888 to 1,352, and training R-squared improved to 0.82. Test MSE improved to 7,521 with an R-squared of 0.15.

Feature importance analysis revealed that num\_nodes (0.2418) had the highest importance, followed closely by channel\_quality (0.2388), transmission\_probability (0.2386), and capture\_threshold (0.2072). Traffic type had the lowest importance (0.0737). These results align with understanding that network size, channel quality, and transmission strategies significantly impact AoI in IIoT networks.

For three hypothetical network configurations, the model predicted AoI values of 10.80, 13.03, and 17.24. The configuration with moderate transmission probability (0.5), neutral capture threshold, and good channel quality achieved the lowest AoI, while the configuration with very high transmission probability (0.9) but low channel quality resulted in the highest AoI, likely due to increased network contention.

**Analysis and Insights**

Key factors influencing the AoI-PLP trade-off include number of nodes, transmission probability, channel quality, and capture threshold. More nodes create greater channel contention, affecting both metrics. Higher transmission probabilities can reduce AoI but increase network contention and packet loss for deadline-oriented traffic. Better channel quality improves transmission reliability for both traffic types.

Two optimization strategies were proposed. An adaptive transmission policy would dynamically adjust transmission probability based on network conditions—using lower probabilities when channel quality is high to reduce contention while maintaining acceptable AoI, and higher probabilities when channel quality degrades. A priority-based channel access scheme would assign higher priority to deadline-oriented traffic during access, ensuring critical packets meet deadlines while allowing AoI-oriented traffic to maintain freshness during non-critical periods.

Real-world applications include smart manufacturing environments with both process monitoring (AoI-oriented) and safety systems (deadline-oriented), where understanding the AoI-PLP trade-off would enable optimizing wireless sensor networks for both production efficiency and worker safety. Similarly, in connected vehicles, the insights could improve both traffic efficiency and safety by balancing awareness of surroundings (AoI-oriented) with reliable delivery of collision warnings (deadline-oriented).

**Deep Learning Model Comparison**

The deep learning model achieved an overall MSE of 3,040 with an R-squared of 0.36, outperforming the Random Forest model's test R-squared of 0.15. The neural network's ability to predict both AoI and PLP simultaneously provides a significant advantage for optimizing both metrics in real-world applications. However, the Random Forest model offers clearer feature importance insights for understanding factors affecting AoI, while the neural network operates more as a "black box." The higher R-squared value of the deep learning model suggests better generalization to unseen data, making it more reliable for predicting the AoI-PLP trade-off in new network configurations.