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**Industrial Internet of Things (IIoT) Network Analysis:**

**Age of Information and Reliability Trade-offs**

**Conceptual Understanding**

Age of Information (AoI) is a key concept in Industrial Internet of Things (IIoT) networks that reflects how fresh or up-to-date the data is when it reaches a central controller or decision-making system. Unlike traditional network metrics like latency or throughput, AoI focuses on the relevance of the data in time-sensitive environments. In IIoT systems, where real-time monitoring and automated responses are critical, outdated information can lead to poor decisions or system failures. For example, in a manufacturing plant, if temperature or pressure sensor readings arrive too late, the system may fail to trigger a necessary shutdown, leading to equipment damage or safety hazards.

Within these networks, there are typically two types of traffic: AoI-oriented traffic and deadline-oriented traffic. AoI-oriented traffic involves continuous, periodic updates that aim to keep the controller constantly informed with the freshest data possible — such as routine sensor readings for environmental conditions. On the other hand, deadline-oriented traffic involves less frequent but highly urgent messages that must be delivered within strict time windows, such as emergency alerts for equipment malfunctions or safety violations. A real-world example of AoI-oriented traffic could be a system tracking air quality in a smart building, whereas deadline-oriented traffic might be a fire alarm signal that must be processed immediately to trigger sprinklers.

Understanding the distinction between these traffic types — and the role of AoI in both — is crucial for designing IIoT networks that are both responsive and reliable.

**Data Exploration and Visual Insights**

As I explored the dataset and visualized different relationships, I noticed a few interesting patterns that helped me better understand how network parameters influence Age of Information (AoI) and Packet Loss Probability (PLP):

*AoI increases when transmission probability is low.*

From the scatter plot of transmission\_probability vs age\_of\_information, there was a clear trend that nodes with lower transmission probabilities tend to have higher AoI. This makes sense because if nodes transmit less frequently, the central controller has to wait longer for updates, which means the information becomes stale faster. It taught me that increasing transmission attempts can help keep the data fresh — but I’m guessing it might also increase interference, so there’s a trade-off.

*Deadline-oriented traffic shows more variation in AoI.*

In the box plot comparing AoI by traffic\_type, the deadline-oriented traffic had a wider spread in AoI. Some of the values were much higher than those for AoI-oriented traffic. I think this reflects how deadline-oriented packets either arrive on time or not at all — so when they do arrive late, the AoI spikes hard. It made me realize that even though deadline traffic is “urgent,” it can be less predictable if the network isn’t optimized.

*Packet loss is strongly correlated with higher AoI.*

From the correlation heatmap, packet\_loss\_probability had the strongest positive correlation with age\_of\_information. This means when more packets are dropped, the controller receives updates less often, and the information becomes outdated. It really highlighted how critical reliability is in IIoT systems. I hadn't thought much about packet loss before this assignment, but now I see how it plays a major role in data freshness.

The trends I found suggest that keeping AoI low requires a careful balance: increasing transmission helps, but only if the network can handle it. At the same time, reducing packet loss seems to be the most important thing to improve both AoI and overall reliability (PLP).

**Machine Learning Model Results**

We trained a Random Forest Regressor to predict Age of Information (AoI), and the model achieved the following performance:

*Mean Squared Error (MSE): ~873,969.29*

MSE measures the average squared difference between the predicted and actual AoI values. While this number may seem large, it's important to remember that it's squared and reflects the variability in time-based measurements. A lower MSE is always better, but it should be interpreted alongside other metrics like R².

*R-squared (R²): 0.603*

This means the model explains approximately 60.3% of the variance in AoI across the dataset. While not perfect, it indicates that the model has captured meaningful patterns and relationships between features and AoI.

Overall, the model performs reasonably well considering the complexity of IIoT network dynamics. It’s strong enough to provide actionable insights into what affects AoI the most, but there is still room for improvement — possibly by adding more features, tuning parameters, or using more advanced modeling techniques

Here are the top 5 features with a significant impact on AoI and what they tell us:

| **Feature** | **Importance** | **Interpretation** |
| --- | --- | --- |
| packet\_loss\_probability | **~76%** | By far the most important factor. Higher packet loss leads to delayed or missing updates, significantly increasing AoI. |
| transmission\_probability | **~6.7%** | How often nodes attempt to send updates. Lower probabilities mean less frequent updates, leading to stale data. |
| traffic\_type\_deadline-oriented | **~5.9%** | Deadline-oriented traffic behaves differently than AoI-optimized traffic, contributing to changes in AoI patterns. |
| channel\_quality | **~4.5%** | Poor channel conditions increase the chance of failed transmissions, raising AoI. |
| capture\_threshold | **~1.7%** | Affects whether signals are successfully decoded — high thresholds make it harder to receive updates, increasing AoI. |

**Analysis and Real-World Applications**

This section explores how different network parameters impact the trade-off between data freshness (AoI) and reliability (PLP), and proposes strategies and real-world applications based on the findings from our analysis and machine learning model.

*Key Factors Influencing the AoI–PLP Trade-off*

Based on the data analysis and machine learning results from the notebook, several network parameters stand out as major influencers of the Age of Information (AoI) and its trade-off with Packet Loss Probability (PLP). The most important factor identified by the model was packet loss probability, which had the highest feature importance in predicting AoI. When packets are frequently lost, the central controller receives updates less often, resulting in stale or outdated information. This directly increases AoI and reduces the reliability of the network.

Traffic type also played a meaningful role. The model showed that deadline-oriented traffic behaves differently from AoI-oriented traffic, introducing more variability in AoI due to the stricter timing constraints and possible packet drops. Finally, channel quality and capture threshold impacted reliability. Poor signal conditions or overly strict capture thresholds reduced the likelihood of successful transmissions, again contributing to higher AoI and PLP.

These factors highlight the importance of balancing network access probability, transmission reliability, and traffic scheduling in order to maintain both data freshness and delivery guarantees in heterogeneous IIoT environments.

*Strategies to Optimize Network Performance*

To address the AoI–PLP trade-off, the following two strategies could be effective:

1. Adaptive Retransmissions for Deadline-Oriented Traffic (TD)

During periods of interference or congestion, dynamically adjusting retransmission attempts for critical TD packets can improve reliability without overwhelming the network. Since TD packets are time-sensitive, increasing their priority when PLP is high can help ensure they are received before expiration, lowering packet loss without significantly increasing AoI for other traffic types.

1. Scheduled Transmissions for AoI-Oriented Traffic (TAoI)

Instead of allowing all nodes to transmit at will, assigning time slots or implementing a round-robin schedule can reduce collisions and improve channel utilization. By avoiding peak traffic periods, this method helps keep AoI low while preserving bandwidth for deadline-sensitive messages. This aligns with the observed trend that transmission probability and traffic overlap affect AoI stability.

*Real-World IIoT Applications of AoI–PLP Trade-off Insights*

1. Predictive Maintenance in Manufacturing

In a smart factory, sensors constantly monitor equipment conditions like temperature or vibration. If AoI is too high, the data becomes outdated and predictive algorithms may fail to detect early signs of malfunction. By minimizing packet loss and ensuring regular updates, system operators can make timely maintenance decisions and avoid costly breakdowns.

1. Smart Grids and Energy Management

In power distribution networks, real-time feedback on load levels and voltage fluctuations is essential for automated control. If messages are delayed or lost (high PLP), the grid might not respond quickly to changes, leading to blackouts or inefficiencies. Applying AoI-optimized strategies ensures that control systems receive fresh data for fast, reliable responses.

**Conclusion**

Through this analysis, we explored the Age of Information (AoI) and its trade-off with Packet Loss Probability (PLP) in Industrial Internet of Things (IIoT) networks. Using data exploration techniques and a machine learning model (Random Forest Regressor), we identified that packet loss, traffic type, and channel conditions significantly influence AoI. The model helped highlight how certain parameters impact data freshness and delivery reliability, reinforcing concepts introduced in the assigned research paper.

We also proposed optimization strategies—such as adaptive retransmissions and scheduled transmissions—to balance real-time data requirements with network constraints. Finally, by connecting these insights to real-world scenarios like predictive maintenance and smart grids, we demonstrated the practical value of understanding and managing the AoI–PLP trade-off in IIoT systems.

This project deepened our understanding of network behavior in heterogeneous traffic environments and showed how data science can be applied to solve real-time communication challenges in industrial settings.

**References**

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