Impact of Random Waypoint Mobility on Age of Information and Energy Efficiency in Energy-Constrained IIoT Networks.

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Abstract

The increasing mobility of devices in Industrial Internet-of-Things (IIoT) environments introduces new challenges in maintaining data freshness and energy efficiency. This work presents an analytical study on how user mobility influences Age of Information (AoI) and Energy Efficiency (EE) in energy-constrained IIoT networks. The system employs an energy-harvesting CR-NOMA uplink and a reinforcement learning (RL)–based downlink scheduler, where the decision-making process is guided by Proximal Policy Optimization (PPO). The secondary user follows a Random Waypoint Model (RWM) to emulate realistic mobility, allowing analysis of how varying movement speeds influence network performance. Simulation results show that as user speed increases, AoI worsens while EE decreases due to rapid channel variations and reduced transmission stability. These findings emphasize the need for mobility-aware scheduling and adaptive RL policies to sustain reliable and efficient communication in dynamic IIoT environments.

Ⅰ. Introduction

The Industrial Internet-of-Things (IIoT) has revolutionized modern industries by enabling intelligent monitoring, predictive maintenance, and autonomous operation through dense networks of sensors and connected devices. These systems must operate efficiently under strict energy constraints while ensuring that transmitted data remains timely and relevant. Therefore, maintaining an optimal balance between Energy Efficiency (EE) and Age of Information (AoI) has become a crucial performance objective in next-generation IIoT networks.

Recent advancements in Cognitive Radio Non-Orthogonal Multiple Access (CR-NOMA) and Reinforcement Learning (RL) [1] have provided promising solutions for this dual optimization problem. Previous work demonstrated that a joint CR-NOMA and RL-based framework [2] can effectively manage both energy consumption and data freshness, using Proximal Policy Optimization (PPO) for adaptive scheduling at the edge node. However, their model assumed a static environment with fixed user positions and stable channel conditions, which limits its applicability to real industrial scenarios.

In practical IIoT systems, devices such as mobile robots,

drones, and automated guided vehicles frequently move across factory environments. This mobility introduces rapid channel variations, intermittent link degradation, and fluctuating energy-harvesting opportunities, all of which affect both EE and AoI. To address this limitation, the present study extends the static CR-NOMA and RL framework by incorporating mobility through a Random Waypoint (RWP) Model [3]. This addition enables a realistic analysis of how user movement impacts communication stability and the RL scheduler's performance in maintaining fresh and energy-efficient data transmission.

This study investigates system behavior under different mobility levels and highlights how increasing movement speeds affects both EE and AoI and the findings provide valuable insight into designing mobility-aware learning mechanisms for reliable and sustainable IIoT communication in dynamic environments.

Ⅱ. Proposed Method

We consider an energy-harvesting Industrial IoT (IIoT) network consisting of multiple sensors communicating with a cache-enabled edge node (EN). The EN is responsible for maintaining real-time data freshness for user requests while ensuring efficient energy utilization across the network. Each communication frame is divided into two phases:

1. Uplink Transmission, in which energy-harvesting sensors (EHSs) send their collected data to the EN; and

2. Downlink Scheduling, where the EN decides whether to deliver freshly updated information or cached data to the user, depending on system conditions.

The EN's scheduling policy is governed by a PPO-based DRL framework that aims to jointly optimize Age of Information (AoI) and Energy Efficiency (EE) while adapting to time-varying network dynamics.

In contrast to previous static frameworks, this study introduces mobility into the system through the RWP model. Under this model, the secondary user moves within the network area by repeatedly selecting a random destination, traveling toward it at a constant speed, pausing briefly, and then choosing a new destination. This process generates realistic, non-linear trajectories that reflect the motion patterns of mobile industrial robots, autonomous guided vehicles, or inspection drones operating in smart-factory environments.

Ⅲ. Results

The secondary user's speed is varied across three conditions — 0 m/s, 1 m/s, and 2 m/s — to analyze the impact of movement on communication stability and learning-based scheduling. As mobility increases, the wireless channel experiences faster fluctuations, causing the received signal strength to change more frequently. These fluctuations lead to time-selective fading and reduced channel predictability, which in turn affect both the EE and the AoI as shown in Fig 1.

IV. Conclusion

This study presented a mobility-aware analysis of AoI optimization in energy-constrained IIoT networks by extending the CR-NOMA and RL-based framework to include the RWP Mobility Model. The results demonstrate that increasing mobility leads to a rise in AoI and a decline in EE, primarily due to rapid channel variations and unstable link quality.

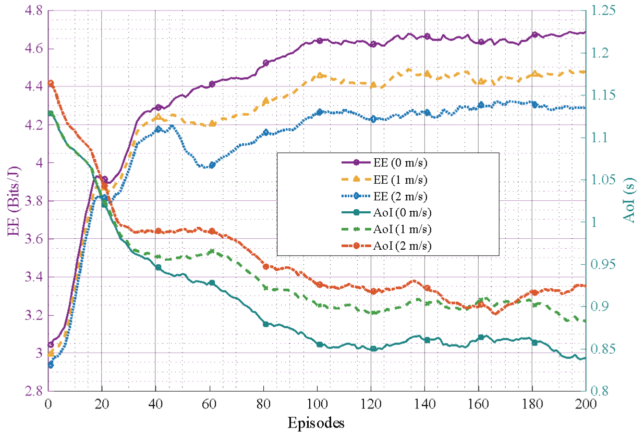

Fig. 1. AoI and EE performance versus user speed (0 m/s, 1 m/s, 2 m/s) under RWP model.

These findings underline the importance of incorporating mobility-awareness into scheduling algorithms and adaptive learning strategies for reliable and energy-efficient IIoT communication. Future work will focus on online RL adaptation and trajectory prediction to mitigate mobility-induced degradation and sustain long-term network performance.

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