DRL-Based Delay-Aware Joint DRX–BWP–WUS Adaption for Energy-Efficient UEs

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Abstract

Discontinuous reception (DRX), bandwidth part (BWP) adaptation, and wakeup signaling (WUS) are effective mechanisms for improving user equipment (UE) energy efficiency in modern and future wireless systems. However, independent configuration of these mechanisms may lead to suboptimal performance under diverse quality-of-service (QoS) requirements. In this paper, we propose a deep reinforcement learning (DRL)-based QoS-aware joint DRX–BWP–WUS adaptation framework that enables intelligent coordination of time-domain sleep control, frequency-domain bandwidth allocation, and wake-up signaling. Simulation results show that the proposed approach significantly improves UE energy efficiency and reduces unnecessary wakeups while preserving QoS, demonstrating its suitability for beyond-5G and future wireless networks.

Ⅰ. Introduction

Energy-efficient operation of user equipment (UE) is essential for reducing operational costs and supporting sustainable wireless networks, particularly for battery-powered devices under dynamic traffic conditions. To improve UE energy efficiency, modern systems employ discontinuous reception (DRX), bandwidth part (BWP) adaptation, and wake-up signaling (WUS) using low-power wake-up receivers (LPWUR). While these mechanisms can individually reduce power consumption, their independent configuration often leads to inefficient trade-offs between energy saving and quality-of-service (QoS).

Joint optimization of DRX, BWP, and WUS is challenging due to their strong interaction and the time-varying nature of traffic and QoS requirements. Static or heuristic approaches are therefore insufficient to achieve optimal performance. In this paper, we propose a deep reinforcement learning (DRL)-based QoS-aware joint DRX–BWP–WUS adaptation framework that dynamically coordinates sleep control, bandwidth allocation, and wake-up signaling. Simulation results demonstrate that the proposed approach significantly improves UE energy efficiency while maintaining QoS, making it suitable for future wireless systems.

II. SYSTEM MODEL AND PROBLEM FORMULATION

We consider a downlink system serving a set of user equipment's (UEs) $\boldsymbol{\mathcal{U}}$. Downlink packets destined for UE $\boldsymbol{u} \in \boldsymbol{\mathcal{U}}$ arrive at the core network according to a stochastic process and are buffered at the base station. Each packet $\boldsymbol{i}$ is time-stamped upon arrival and associated with a packet delay budget (PDB) determined by its QoS class. The age of information (AoI) of packet $\boldsymbol{i}$ at time $\boldsymbol{t}$ is defined as

$$\mathbf{AoI}_i(\boldsymbol{t}) = \boldsymbol{t} - \boldsymbol{t}_i^{\mathbf{arr}},$$

where $\boldsymbol{t}_i^{\mathbf{arr}}$ denotes the packet arrival time.
Scheduling urgency is quantified using the time-to-schedule (TTS) metric

$$\mathbf{TTS}_i(\boldsymbol{t}) = \mathbf{PDB}_i - \mathbf{AoI}_i(\boldsymbol{t}),$$

where packets with smaller $\mathbf{TTS}$ values are prioritized.

Each UE operates under a discontinuous reception (DRX) mechanism with a fixed cycle length $\boldsymbol{T}_{\mathbf{DRX}}$, consisting of an active window, multiple listening occasions (LOs), and a sleep period. During sleep or dormant states, the UE periodically activates a (LPWUR) to monitor wake-up signals (WUS). Detection of a WUS triggers activation of the main RF receiver and transition to the active state.

At each discrete time instant $\boldsymbol{t}$, UE $\boldsymbol{u}$ is characterized by a binary activity state $\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t})$, where:

$$\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t}) = \begin{cases} \mathbf{1}, & \text{UE active,} \\ \mathbf{0}, & \text{UE sleeping/dormant.} \end{cases}$$

The instantaneous power consumption of UE $\boldsymbol{u}$ is modeled as

$$\begin{aligned} \boldsymbol{P}_{\boldsymbol{u}}(\boldsymbol{t}) &= \boldsymbol{P}_{\mathbf{sleep}} \mathbf{1}\{\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t}) = \mathbf{0}\} + \boldsymbol{P}_{\mathbf{act}} \mathbf{1}\{\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t}) = \mathbf{1}\} \\ &+ \boldsymbol{P}_{\mathbf{LPWUR}} \mathbf{1}\{\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t}) = \mathbf{0}, \boldsymbol{t} \in \boldsymbol{\mathcal{L}}\} + \boldsymbol{P}_{\mathbf{PDCCH}} \mathbf{1}\{\boldsymbol{S}_{\boldsymbol{u}}(\boldsymbol{t}) = \mathbf{1}, \boldsymbol{t} \in \boldsymbol{\mathcal{M}}_{\boldsymbol{u}}\} \\ &+ \boldsymbol{P}_{\mathbf{sw}} \boldsymbol{\Sigma}_{\boldsymbol{u}}(\boldsymbol{t}), \end{aligned}$$

where $\boldsymbol{\mathcal{M}}_{\boldsymbol{u}}$ denotes the monitoring occasions for control signaling, and $\boldsymbol{\Sigma}_{\boldsymbol{u}}(\boldsymbol{t})$ indicates whether a bandwidth part (BWP) switch occurs at time $\boldsymbol{t}$.

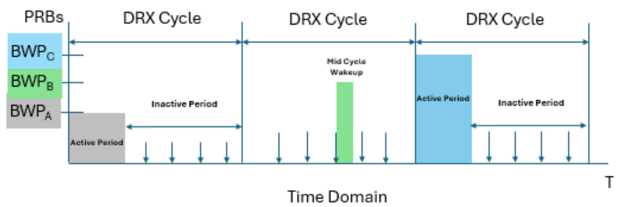


Fig.1. Delay Aware BWP/WUS enabled DRX cycle

III. DRL-BASED JOINT DRX–BWP–WUS ADAPTATION

At each decision epoch $\boldsymbol{t}$, the DRL agent observes the system state, selects a control action, and receives a reward reflecting the trade-off between UE energy consumption and quality-of-service (QoS). The per-UE state is defined as

$$\mathbf{s}_u(t) = [Q_u(t), \overline{\mathrm{TTS}}_u(t), S_u(t), b_u(t), \tau_u(t)],$$

where $Q_u(t)$ denotes the buffered data volume, $\bar{\mathrm{TTS}}_u(t)$ is the minimum time-to-schedule among buffered packets, $S_u(t) \in \{0,1\}$ is the UE activity state, and $b_u(t)$ is the currently active BWP. The global system state is formed by aggregating all UE states.

$$\mathbf{a}_u(t) = [a_u^{\mathrm{DRX}}(t), a_u^{\mathrm{BWP}}(t), a_u^{\mathrm{WUS}}(t)],$$

where $a_u^{\mathrm{BWP}}(t) \in \{\mathrm{BWP}_A, \mathrm{BWP}_B, \mathrm{BWP}_C\}$ and $a_u^{\mathrm{WUS}}(t) \in \{0,1\}$. BWP switching incurs additional delay and energy cost, which is reflected in the reward.

$$r(t) = -[\alpha \sum_u P_u(t) + \beta \sum_{i \in \mathcal{I}(t)} \ell_i(t) + \gamma \sum_u \mathbf{1}\{Q_u(t) > 0, S_u(t) = 0\}],$$

where $P_u(t)$ denotes UE power consumption, $\ell_i(t)$ represents packet loss due to QoS violation, and the third term penalizes buffered packets during sleep. The weights α, β, γ control the energy–QoS trade-off.

We adopt a deep Q-learning (DQN) framework to approximate the optimal action-value function:

$$Q^*(\mathbf{s}, \mathbf{a}) = \mathbb{E}[\sum_{k=0}^{\infty} \gamma^k r(t+k) \mid \mathbf{s}(t) = \mathbf{s}, \mathbf{a}(t) = \mathbf{a}],$$

The network parameters are updated by minimizing the temporary difference loss:

$$\mathcal{L}(\boldsymbol{\theta}) = \mathbb{E}[(r(t) + \gamma \max_{\mathbf{a}'} Q(\mathbf{s}(t+1), \mathbf{a}'; \boldsymbol{\theta}^-) - Q(\mathbf{s}(t), \mathbf{a}(t); \boldsymbol{\theta}))^2]$$

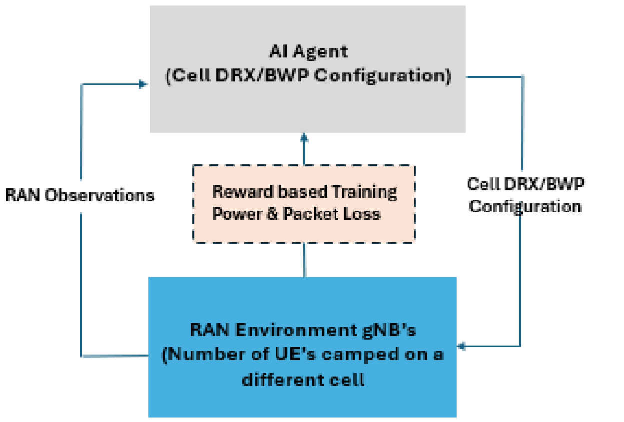


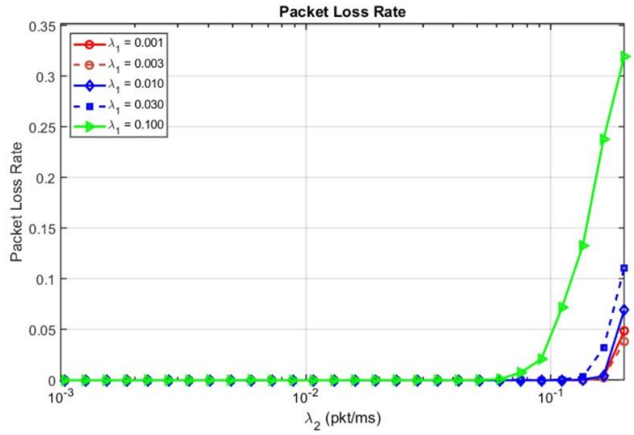
Fig.2. DRL based Cell DRX/BWP Configuration

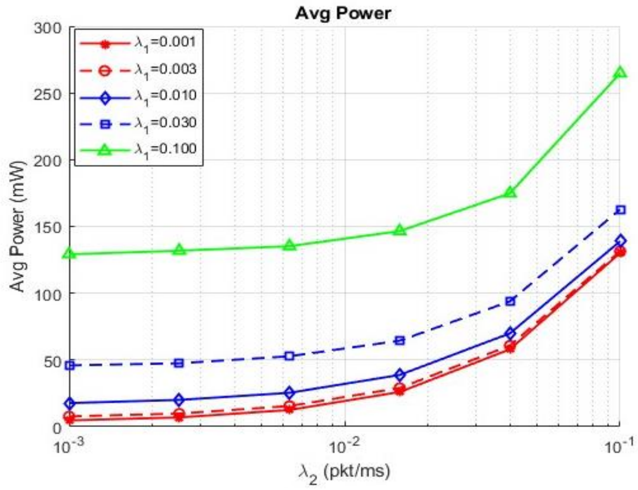
IV. Results and Discussion

Simulation results show that the proposed DRL-based joint DRX–BWP–WUS scheme significantly reduces average UE power consumption while maintaining a low packet loss rate across varying traffic conditions. This confirms its effectiveness in achieving energy-efficient operation without compromising QoS.

IV. Conclusion

This paper presented a DRL-based QoS-aware joint DRX–BWP–WUS adaptation framework for energy-efficient UE operation. By jointly optimizing sleep control, bandwidth allocation, and wake-up signaling, the proposed approach significantly reduces UE power consumption while maintaining low packet loss. These results demonstrate the effectiveness of intelligent joint adaptation for future wireless systems and motivate further extensions toward more complex deployment scenarios.





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