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Uplink puncturing for mixed URLLC and eMBB services in 5G-based IWNs: a model-aided DRL method

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Key words: Uplink 5G networks; Enhanced mobile broadband (eMBB); Ultra-reliable low-latency communication (URLLC); Resource slicing; Puncturing; Deep reinforcement learning (DRL)

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Motivation

1. The coexistence of ultra-reliable low-latency communication (URLLC) and enhanced mobile broadband (eMBB) services in 5G-based industrial wireless networks (IWNs) poses significant resource slicing challenges due to their inherent performance requirement conflicts.
2. In the uplink, the base station (BS) lacks precise information about sporadic URLLC packet arrivals from user equipment (UE), making dynamic and efficient resource allocation difficult.
3. Existing methods like static reservation lead to substantial resource waste for sporadic URLLC traffic, while non-orthogonal multiple access (NOMA) imposes stringent receiver requirements that are hard to meet in industrial scenarios.

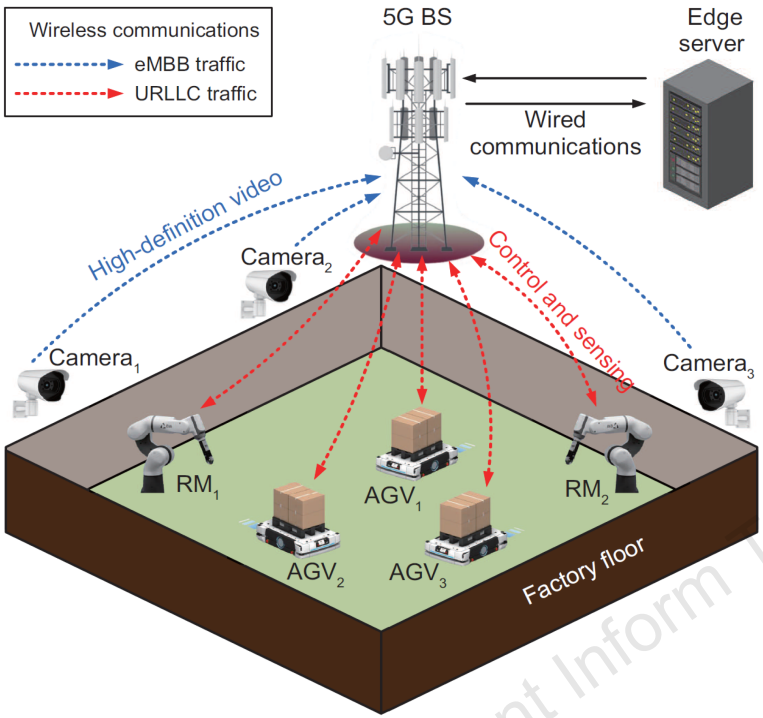
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Main idea

1. We propose a puncturing method that allows sporadic URLLC transmissions to dynamically preempt ongoing eMBB transmissions in the uplink, maximizing eMBB rate under strict URLLC constraints.
2. To enhance URLLC reliability with minimal overhead, we design a Random Repetition Coding-based Contention (RRCC) scheme, enabling packets to select any available resources within their deadline.
3. We develop a model-aided Deep Reinforcement Learning (DRL) framework that jointly optimizes the URLLC repetition number (via the RRCC reliability model) and the eMBB scheduling list for superior resource efficiency and fast convergence.

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System model



1. An industrial automation scenario with 5G-based IWNs, featuring AGVs, RMs, and cameras communicating with the BS for both sporadic URLLC and fully buffered eMBB traffic.

2. Traffic characteristics:

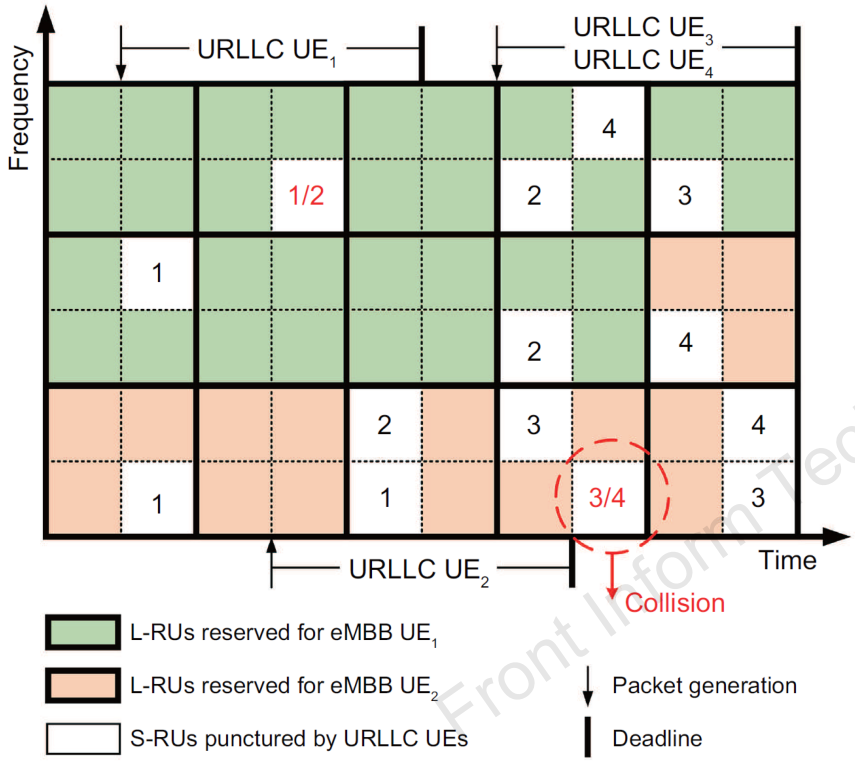
   - URLLC: Sporadic traffic modeled by a Poisson distribution.
   - eMBB: Fully buffered model ensuring continuous packet availability.

3. Wireless channel impairments are considered using Rician fading models to account for multipath propagation effects.

4. Uplink transmission is based on OFDMA with flexible numerology. Resources are organized into Resource Blocks (RBs). eMBB UEs use long TTIs (L-TTIs) for high spectral efficiency, while URLLC packets are transmitted via puncturing within short TTIs (S-TTIs) over the eMBB resources.

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Puncturing method



1. Define puncturing as a mechanism where URLLC packets can preempt ongoing eMBB transmissions via power control adjustments.

2. Formulate optimization problem *P* to maximize eMBB accumulated rate while meeting URLLC reliability requirements.

Key parameters:
- puncturing intensity *K*
- scheduling parameters $S^j_{m,n}(t)$

$$\mathcal{P}: \underset{S^j_{m,n}(t),K(t)}{\text{Maximize}} \sum_{j=1}^{N_e} R^j_e(t)$$

$$R_u(K(t)) \geq \delta,$$

$$r_{m,n}(K(t)) \leq R, \forall m, n,$$

$$1 \leq K(t) \leq \hat{K},$$

$$S^j_{m,n}(t) \in \{0,1\}, \forall m, n, j,$$

$$\sum_{j=1}^{N_e} S^j_{m,n}(t) = 1, \forall m, n.$$

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RRCC scheme for URLLC

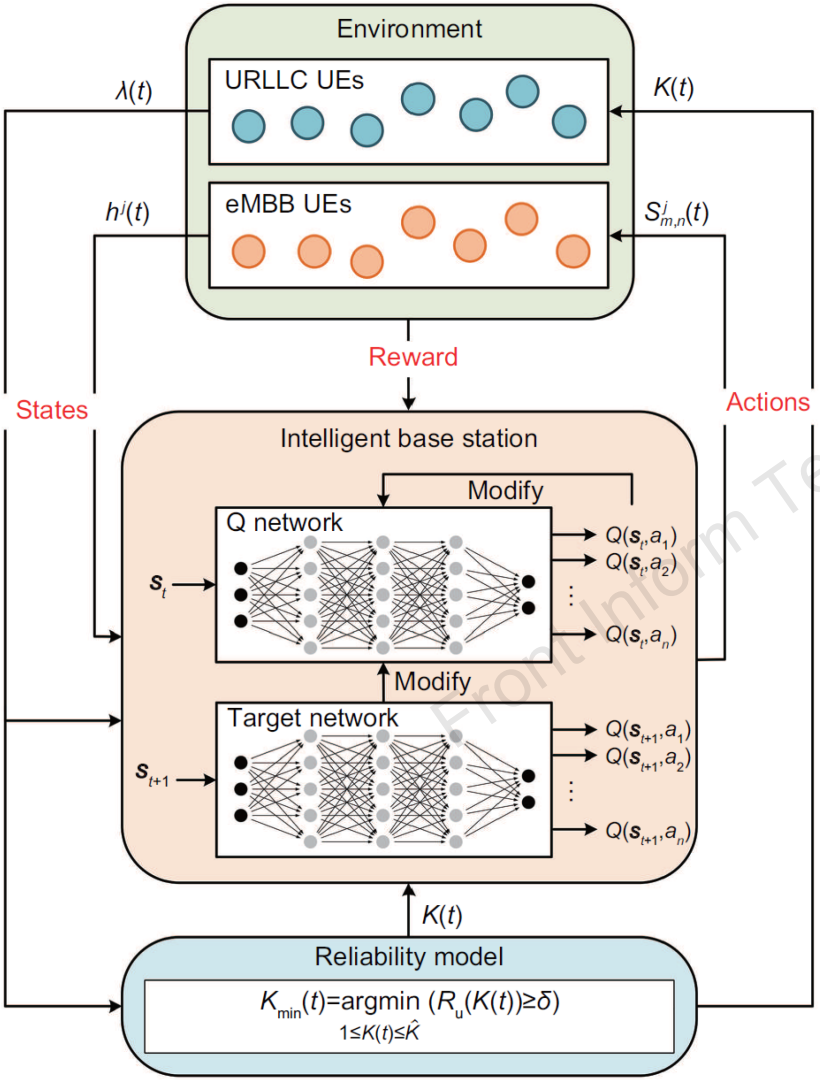
1. Designed a Random Repetition Coding-based Contention (RRCC) scheme for sporadic URLLC traffic, enabling packets to select any available resources within their deadline.
2. Derived an analytical reliability model for RRCC, showing that fewer repetitions are needed compared to existing schemes while achieving the same reliability level.

$$R_{\mathrm{u}}(K)=\sum_{l=1}^{K}(-1)^{l+1}C_{K}^{l}\left(1-P_{\mathrm{a}}(\lambda,T_{\mathrm{u}})+P_{\mathrm{a}}(\lambda,T_{\mathrm{u}})\frac{C_{T_{\mathrm{u}}M_{\mathrm{S}}-l}^{K}I_{T_{\mathrm{u}}M_{\mathrm{S}}-l\geq K}}{C_{T_{\mathrm{u}}M_{\mathrm{S}}}^{K}}\right)^{N_{\mathrm{u}}-1}(1-p)^{l}$$

3. The RRCC scheme is particularly effective in reducing collisions and enhancing transmission reliability under dynamic environments.

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Model-aided DRL solution

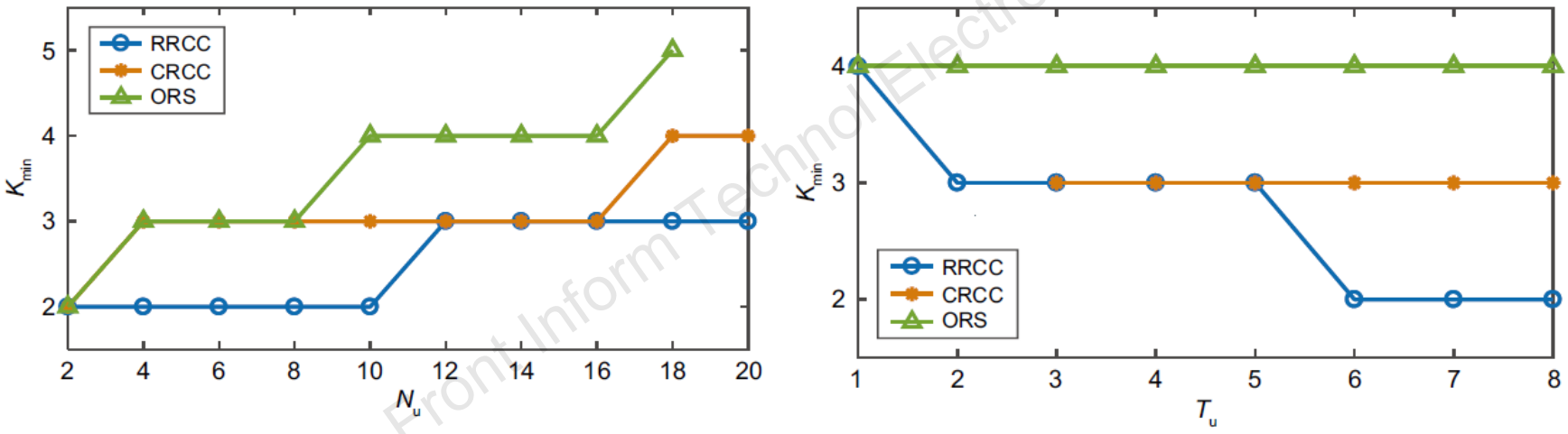


1. Developed a DRL solution based on the reliability model, which jointly optimizes the repetition number of URLLC traffic and the scheduling list of eMBB traffic.
2. This approach dynamically adapts to changing environments, providing effective responsiveness to network conditions.
3. Demonstrated accelerated convergence of the model-aided DRL algorithm through simulations, highlighting its superiority over existing methods in terms of resource efficiency.

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Major results

Comparison of K_{min} under different T_u's among RRCC, CRCC, and ORS schemes (λ=0.005 and δ=0.9999)

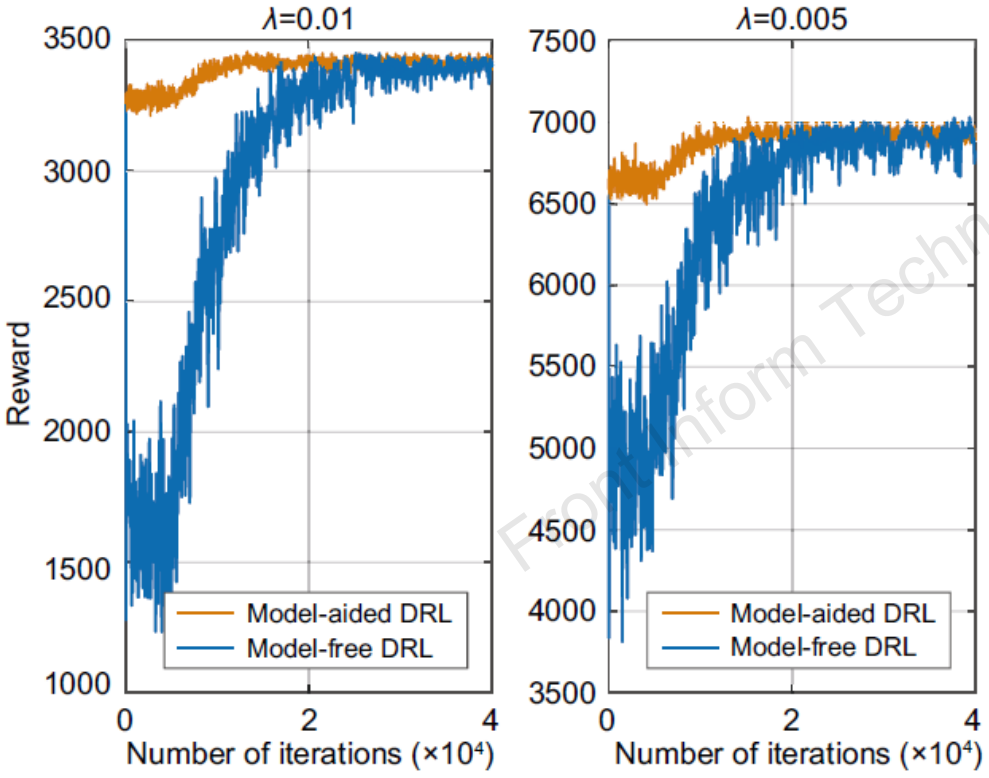


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Compared to other methods, the RRCC method requires the minimum number of repetitions K_{min} to meet the reliability requirement, thereby minimizing the impact of puncturing on eMBB transmission.

Major results

Convergence validation of model-aided DRL

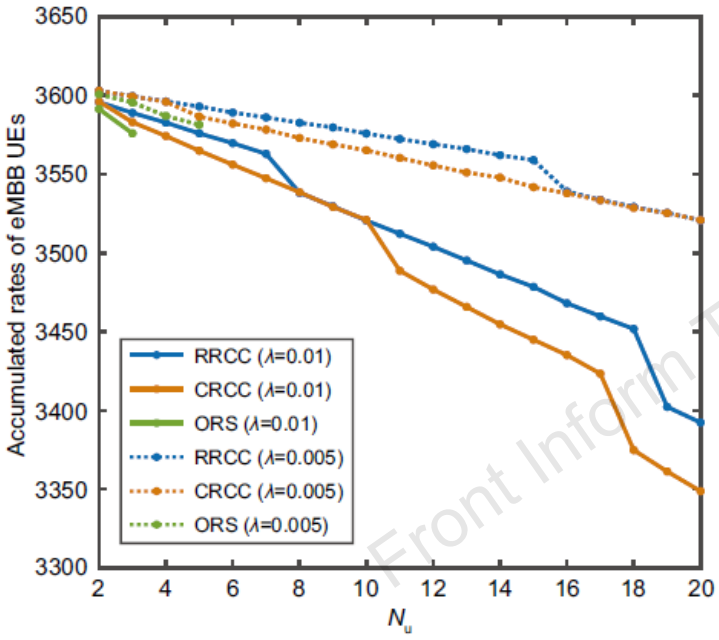


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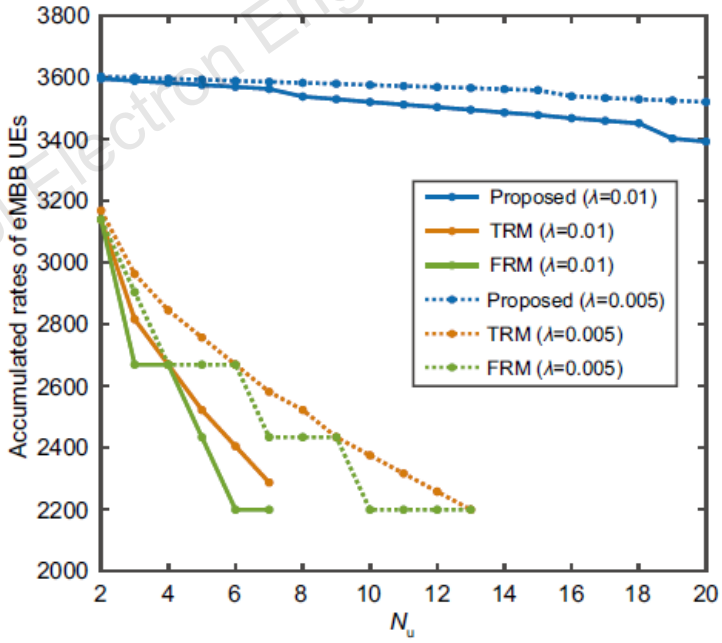
- The model-aided DRL algorithm converges approximately 50% faster than the model-free DRL approach under both λ=0.01 and λ=0.005, demonstrating that integrating the analytical reliability model significantly accelerates learning convergence.
- This improvement is achieved by reducing the action space dimension via the pre-computed minimum repetition number (K_{min}), enabling more efficient exploration.

Major results

Performance analysis of model-aided DRL



The RRCC puncturing method achieves higher eMBB rates than CRCC and ORS, especially with more URLLC users, thanks to fewer repetitions.



The proposed scheme outperforms time-domain (TRM) and frequency-domain (FRM) reservation by using resources flexibly; FRM wastes the most due to static allocation.

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Conclusions

We have investigated the coexistence challenge of URLLC and eMBB in uplink 5G-based IWNs. We propose a puncturing-based method featuring:

- A novel Random Repetition Coding-based Contention (RRCC) scheme for sporadic URLLC traffic, which is proven to be more resource-efficient than baseline schemes.
- A model-aided DRL framework that leverages the analytical RRCC reliability model to jointly optimize URLLC and eMBB scheduling, achieving high resource efficiency and rapid algorithmic convergence.

The proposed method offers a practical and efficient solution for dynamic resource slicing in heterogeneous industrial wireless networks.

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