Predictive Resource Allocation in mmWave Systems with Rotation Detection

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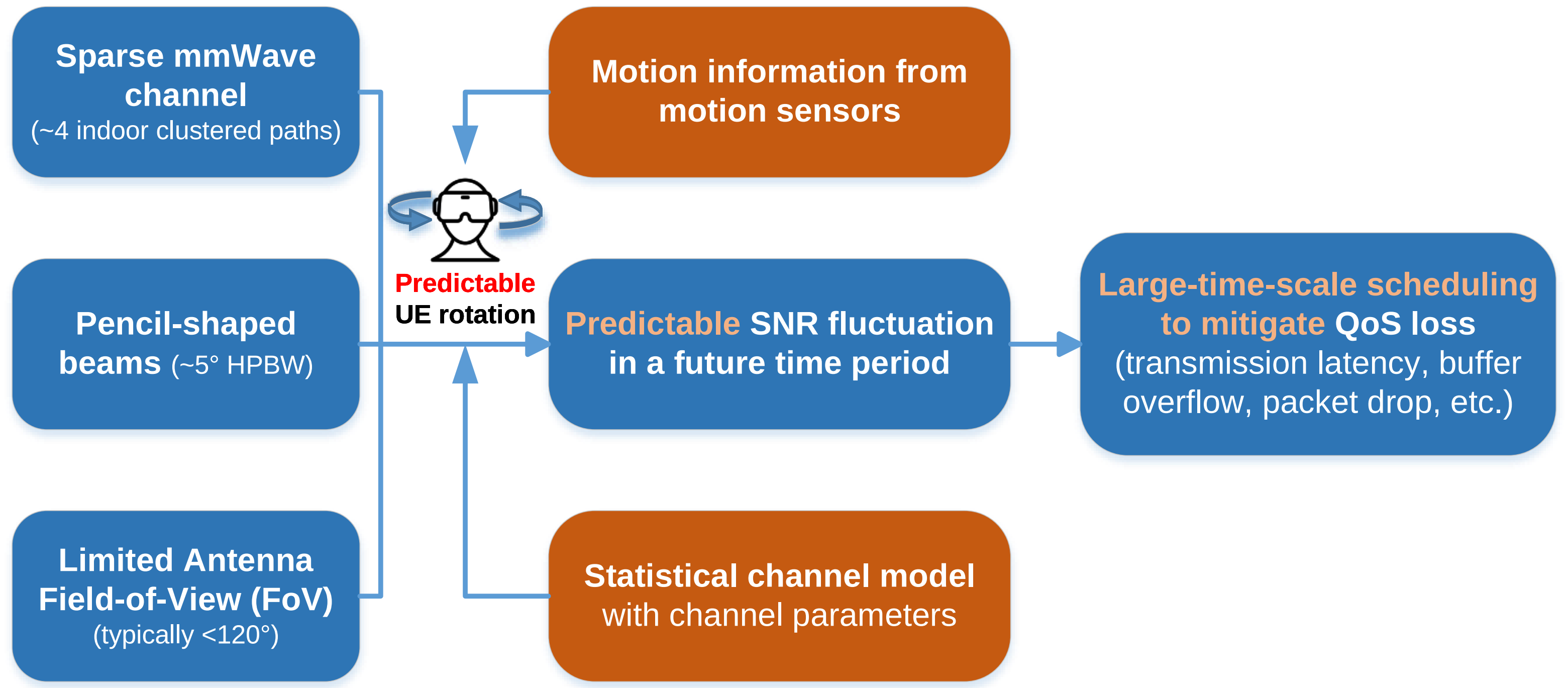
Introduction

Motivation:

① UE rotation may cause significant SNR fluctuation, thus QoS degradation, in mmWave systems.
② UE-embedded motion sensors enable predictive SNR fluctuation with statistical channel model.
③ This raises a new design issue of large-time-scale scheduling with non-stationary but predictable channel statistics.



Sparse mmWave channel (~4 indoor clustered paths)

Pencil-shaped beams (~5° HPBW)

Limited Antenna Field-of-View (FoV) (typically <120°)

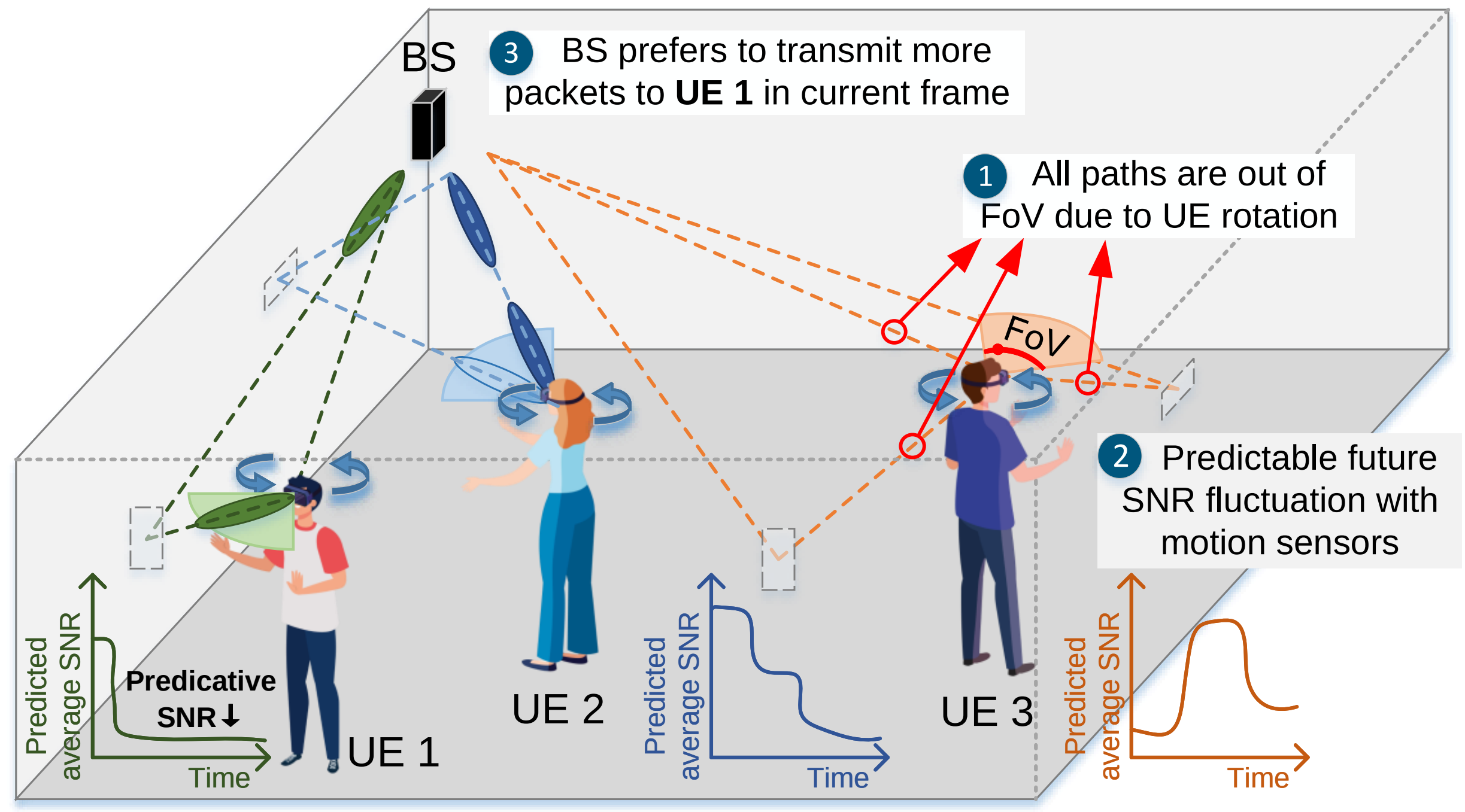
Motion information from motion sensors

Predictable UE rotation

Predictable SNR fluctuation in a future time period

Statistical channel model with channel parameters

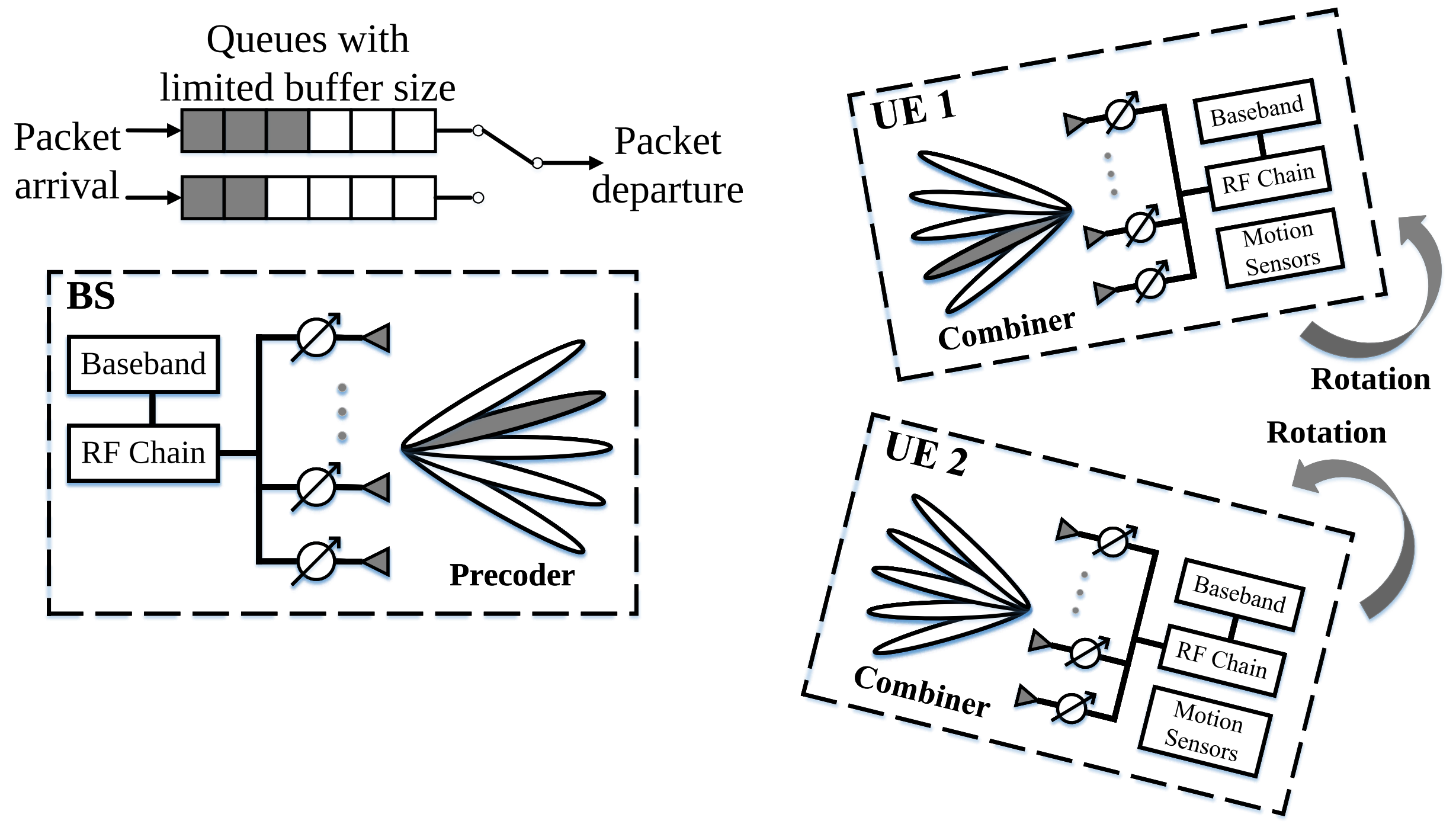
Large-time-scale scheduling to mitigate QoS loss (transmission latency, buffer overflow, packet drop, etc.)



System Model

Network Description:

- Downlink transmission with one BS and K rotating UEs.
- **Predictable UE orientation:** UE orientation in future T frames can be predicted by orientation prediction methods (e.g., constant angular velocity).
- **Analog MIMO transceivers:** each with a single RF chain and a limited-FoV ULA.
- **Finite buffer size:** K downlink queues at the BS each with limited buffer size $Q_{\max}$ and **random arrival**. Buffer overflow will lead to packet drop.



Cluster-based Channel Model:

$$\mathbf{H}_{t,k}=\sum_{i=1}^{N_k^{\mathrm{cl}}}\sum_{\ell=1}^{N_{k,i}^{\mathrm{ray}}}\underbrace{\alpha_{t,k,i,\ell}}_{\text{complex gain}}\underbrace{\mathbf{a}_{\mathrm{R}}(\phi_{t,k,i,\ell})\mathbf{a}_{\mathrm{T}}^{\mathsf{H}}(\theta_{t,k,i,\ell})}_{\text{array responses}}\underbrace{\Lambda_{\mathrm{R}}(\phi_{t,k,i,\ell})\Lambda_{\mathrm{T}}(\theta_{t,k,i,\ell})}_{\textbf{antenna pattens (w/ limited FoV)}}$$

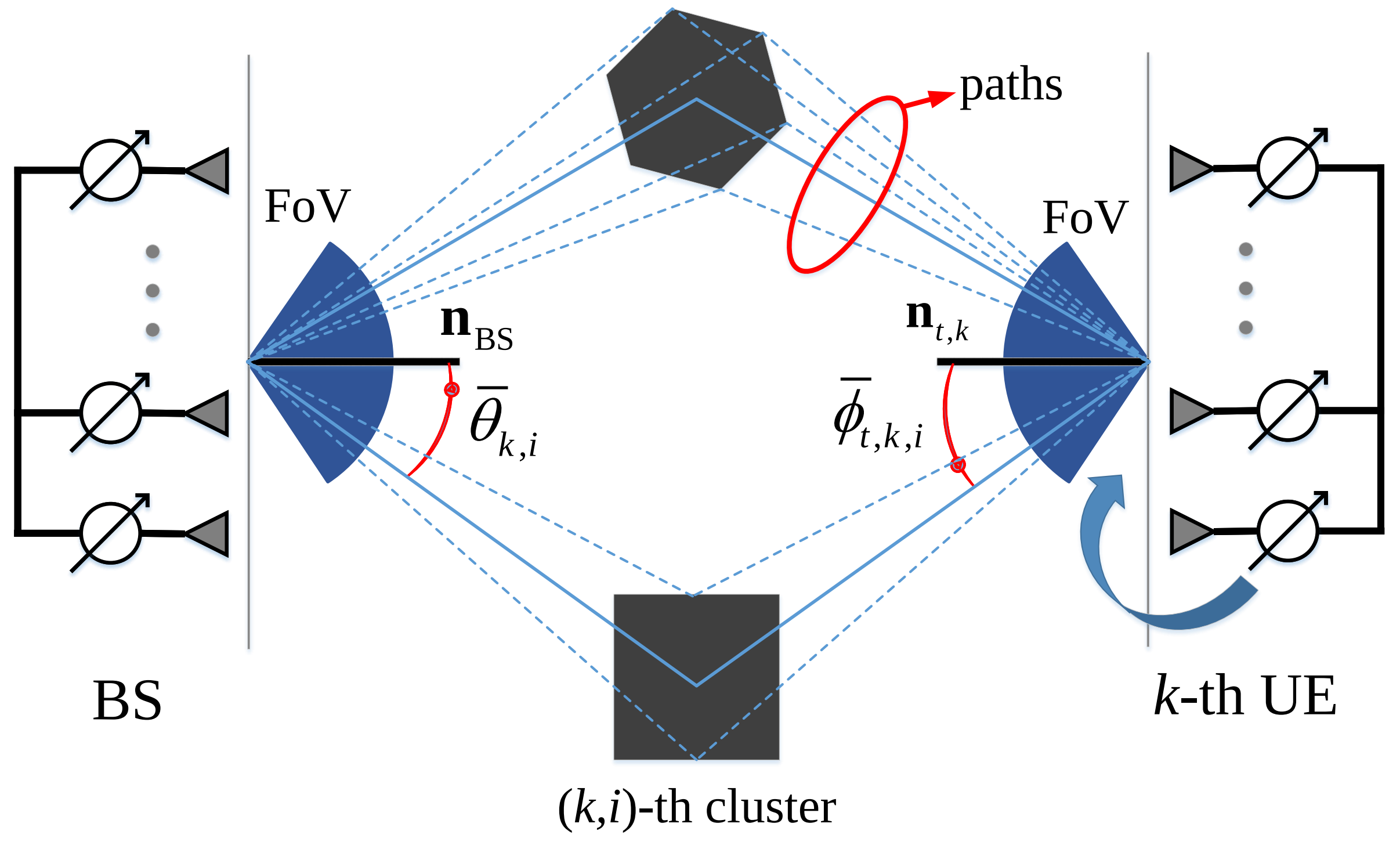
Predictable Average SNR:

- With pre-learned quasi-static statistical channel parameters, the only non-stationary parameter, **cluster mean AoA** $\bar{\phi}_{t,k,i}$ due to UE rotation, can be predicted with constant angular velocity ω_k,

$$\bar{\phi}_{t,k,i}=\bar{\phi}_{1,k,i}+(t-1)\omega_k T_{\mathrm{F}}.$$

- Future average SNR can be predicted by

$$\overline{\mathrm{SNR}}_{t,k}=\mathbb{E}_{\mathbf{H}_{t,k}}\frac{P_{t,k}\left|\mathbf{w}_{t,k}^{\mathsf{H}}\mathbf{H}_{t,k}\mathbf{f}_{t,k}\right|^2}{N_0 W}.$$

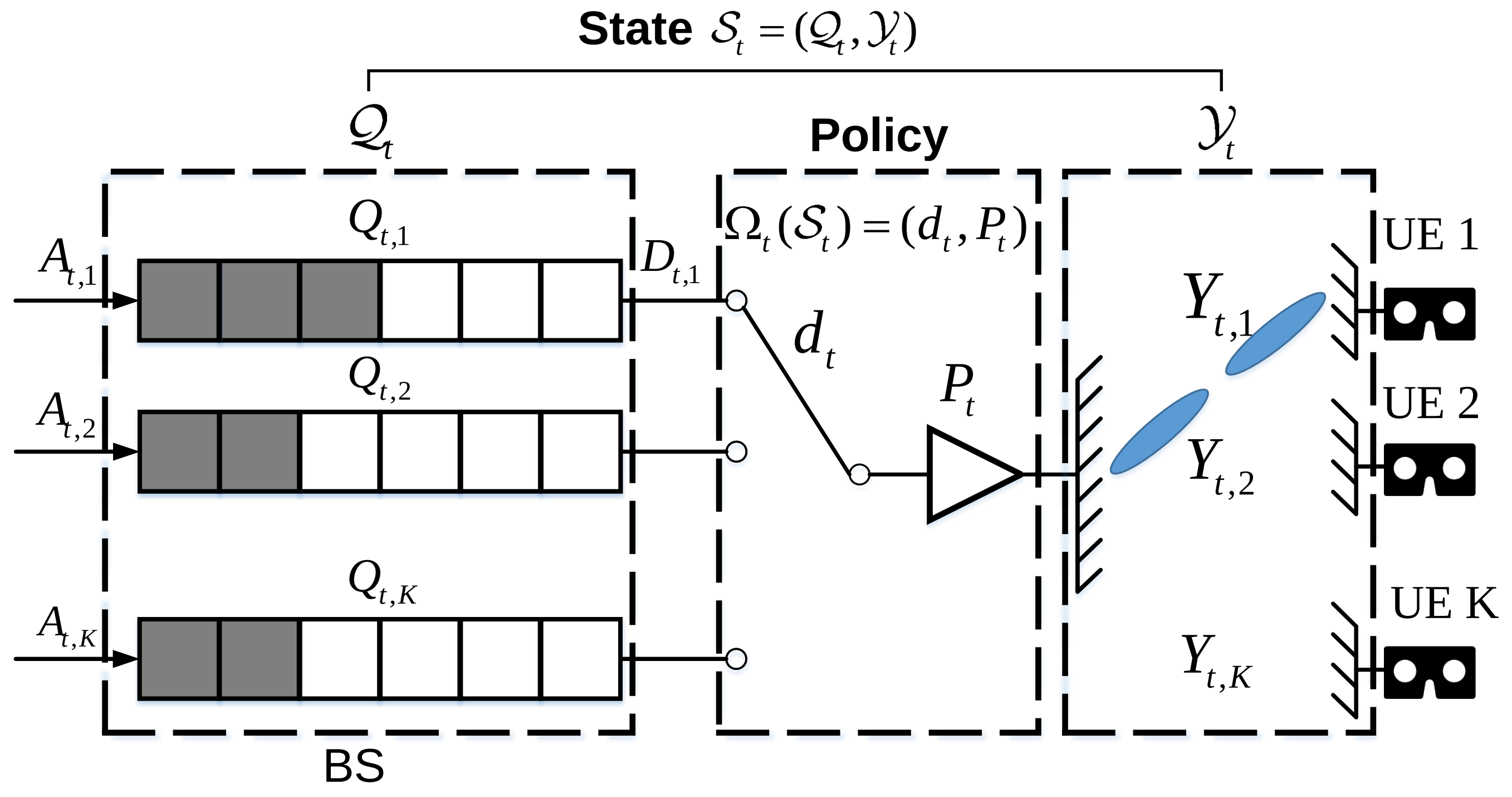


Problem Formulation

Finite-horizon MDP:

- **Finite horizon (stages #):** because the system can predict UE orientation in T frames (one scheduling period).
- **Per-frame cost:**

$$g_t\big(\mathcal{S}_t,\Omega_t(\mathcal{S}_t)\big)\triangleq\underbrace{w_{\mathrm{P}}P_t}_{\substack{\text{downlink power}\\\text{consumption}}}+\sum_{k\in\mathcal{K}}\Big(\underbrace{Q_{t,k}}_{\substack{\text{queue}\\\text{length}}}+\underbrace{w_{\mathrm{Q}}\mathbb{I}[Q_{t,k}=Q_{\max}]}_{\text{packet-drop penalty}}\Big)$$



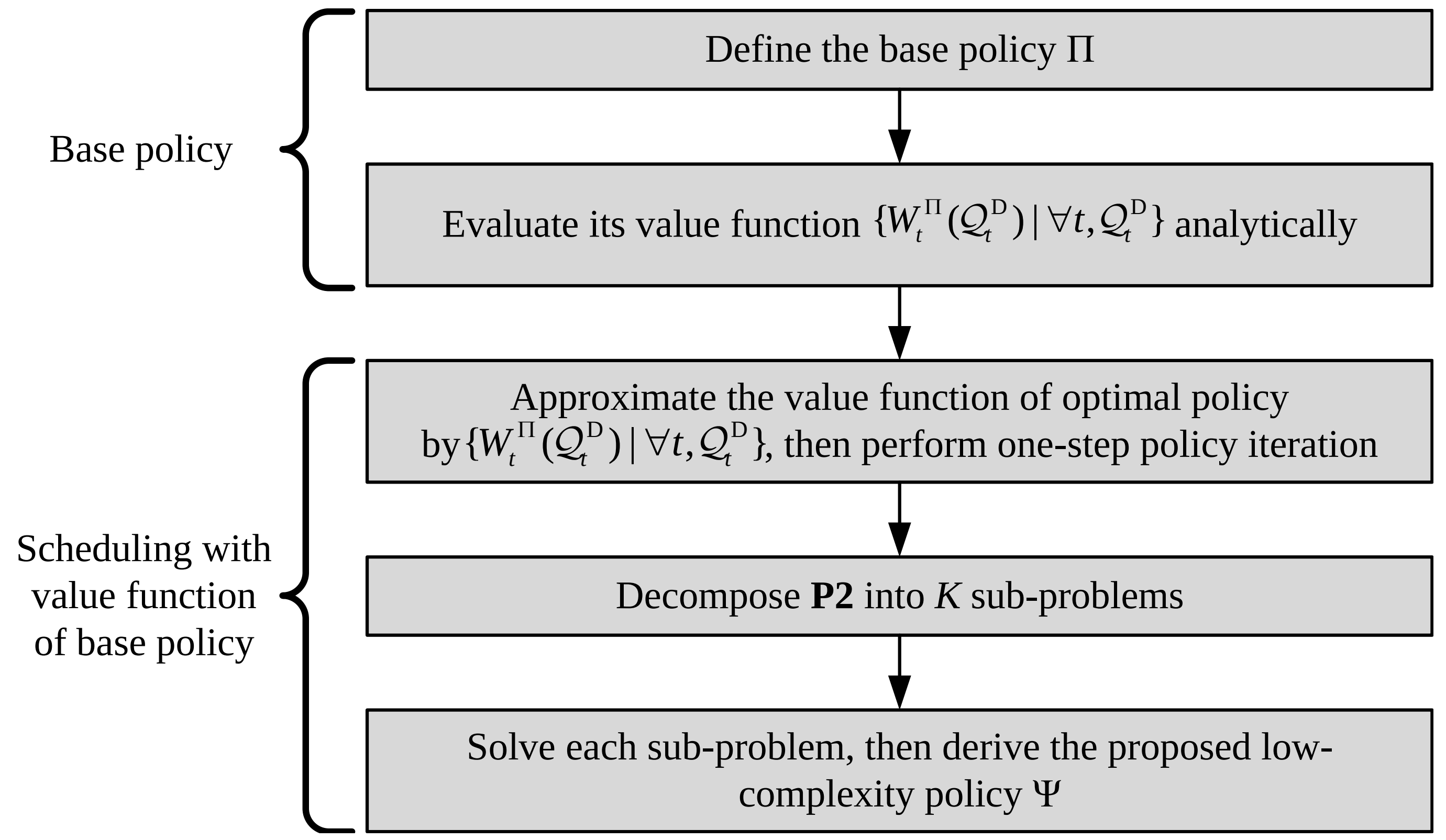
Dynamic Programming Problem:

- To minimize the weighted sum of downlink energy consumption, queuing delay and packet-drop rate in future T frames.

$$\mathbf{P1}:\Omega^{\star}\triangleq\{\Omega_t^{\star}|\forall t\}=\arg\min_{\Omega}\mathbb{E}_{\mathcal{A},\mathcal{Y}}^{\Omega}\Big[\sum_{t=1}^{T}g_t\big(\mathcal{S}_t,\Omega_t(\mathcal{S}_t)\big)\Big|\mathcal{S}_1\Big]$$
$$\text{s.t.}\quad 0\le P_t\le P_{\max},\ \forall t.$$

Proposed Solution

Low-complexity Suboptimal Solution Framework:



Base policy
- Define the base policy Π
- Evaluate its value function $\{W_t^{\Pi}(\mathcal{Q}_t^{\mathrm{D}})\,|\,\forall t,\mathcal{Q}_t^{\mathrm{D}}\}$ analytically

Scheduling with value function of base policy
- Approximate the value function of optimal policy by $\{W_t^{\Pi}(\mathcal{Q}_t^{\mathrm{D}})\,|\,\forall t,\mathcal{Q}_t^{\mathrm{D}}\}$, then perform one-step policy iteration
- Decompose **P2** into K sub-problems
- Solve each sub-problem, then derive the proposed low-complexity policy Ψ

- **Base Policy** Π**:** UE selection based on *backpressure algorithm*, and constant downlink transmission power.
- **One-step policy improvement:**

$$\mathbf{P2}:\Psi_t(\mathcal{S}_t)=\arg\min_{\Omega_t(\mathcal{S}_t)}\Big\{g_t\big(\mathcal{S}_t,\Omega_t(\mathcal{S}_t)\big)+W_t^{\Pi}\big(\mathcal{Q}_t^{\mathrm{D}}(\mathcal{S}_t,\Omega_t)\big)\Big\},$$

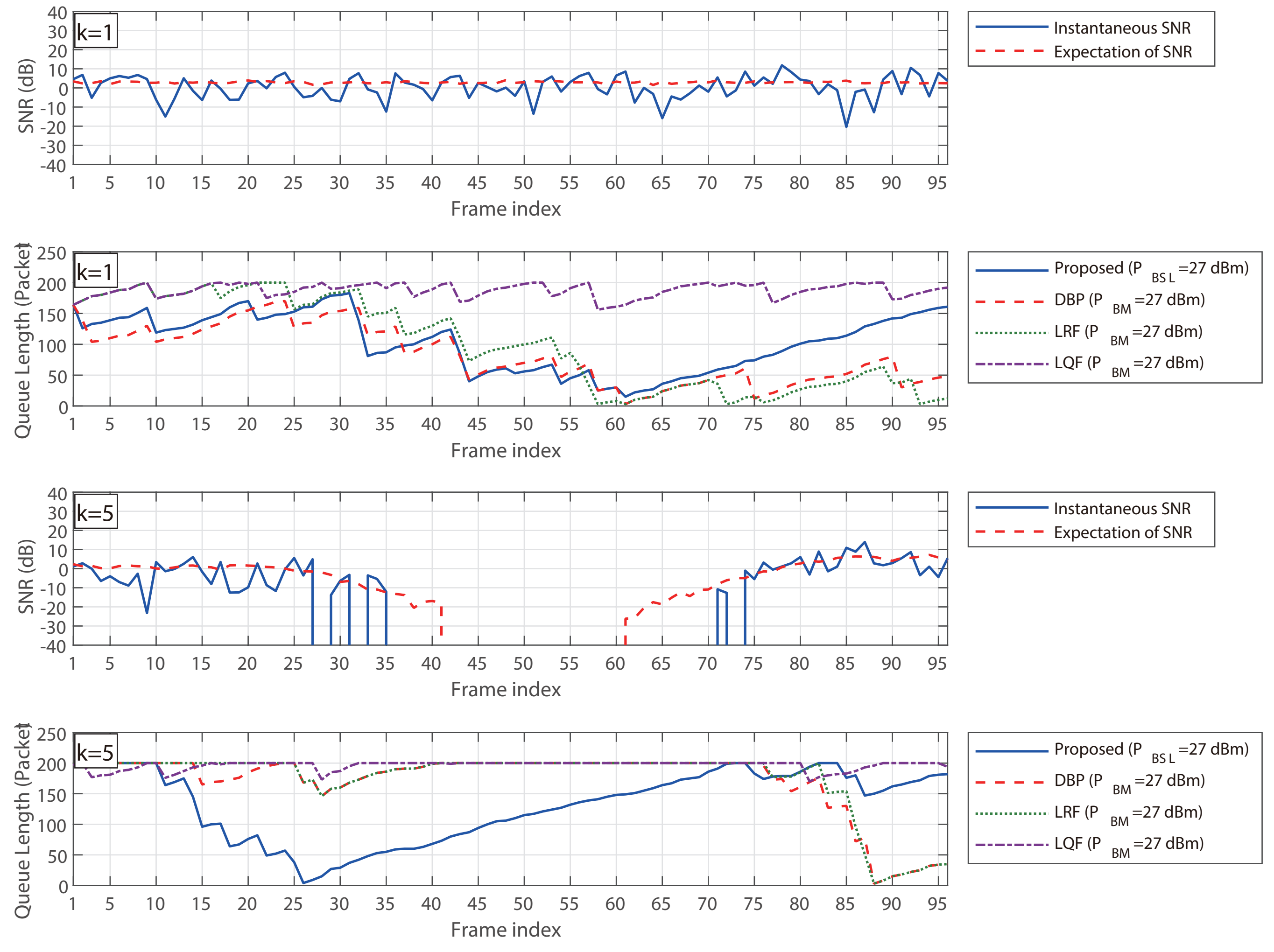
Advantages:

- **Low-complexity:** analytical expressed value function of base policy, and one-step value iteration.
- **Offline base policy evaluation** with reduced state space.
- **Distributed online scheduling** with small signaling overhead.
- **Performance Guarantee:** lower bounded by base policy.

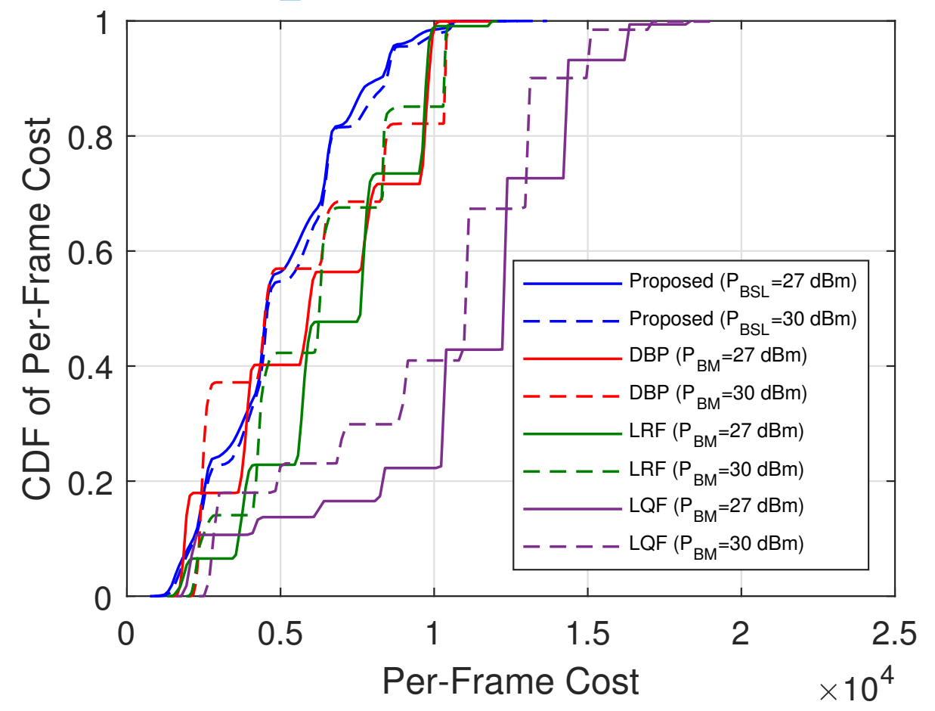
Simulation Results

How it Works: an Illustrative Run

- Instantaneous SNR and queue dynamics of a static UE (k=1) and a rotating UE (k=5).
- The proposed scheme can predictively schedule more transmission opportunities to a rotating UE (k=5) about 20 frames before its SNR degrades, so that the future packet drop rate can be significantly reduced.
- **Benchmarks:**
  Dynamic BackPressure (DBP)
  Largest-Rate First (LRF)
  Longest-Queue First (LQF)



CDF of per-frame cost:



Average component cost: