STARS: STateful Adaptive Rate Selection for Enhanced QoE

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Background and Contribution

Goal: To design and implement an **intelligent ABR streaming system** that optimizes Quality of Experience (QoE) by **dynamically adapting video bitrate** to network fluctuations.

Motivations:

- Traditional ABR algorithms often misinterpret volatile network conditions, leading to **disruptive rebuffering** and **inconsistent video quality**, thereby degrading User Experience.
- Smarter ABR strategies are needed to intelligently analyze **complex network dynamics** and employ proactive, robust measures (e.g., effective panic/recovery) to ensure **playback continuity** and **optimal QoE**.
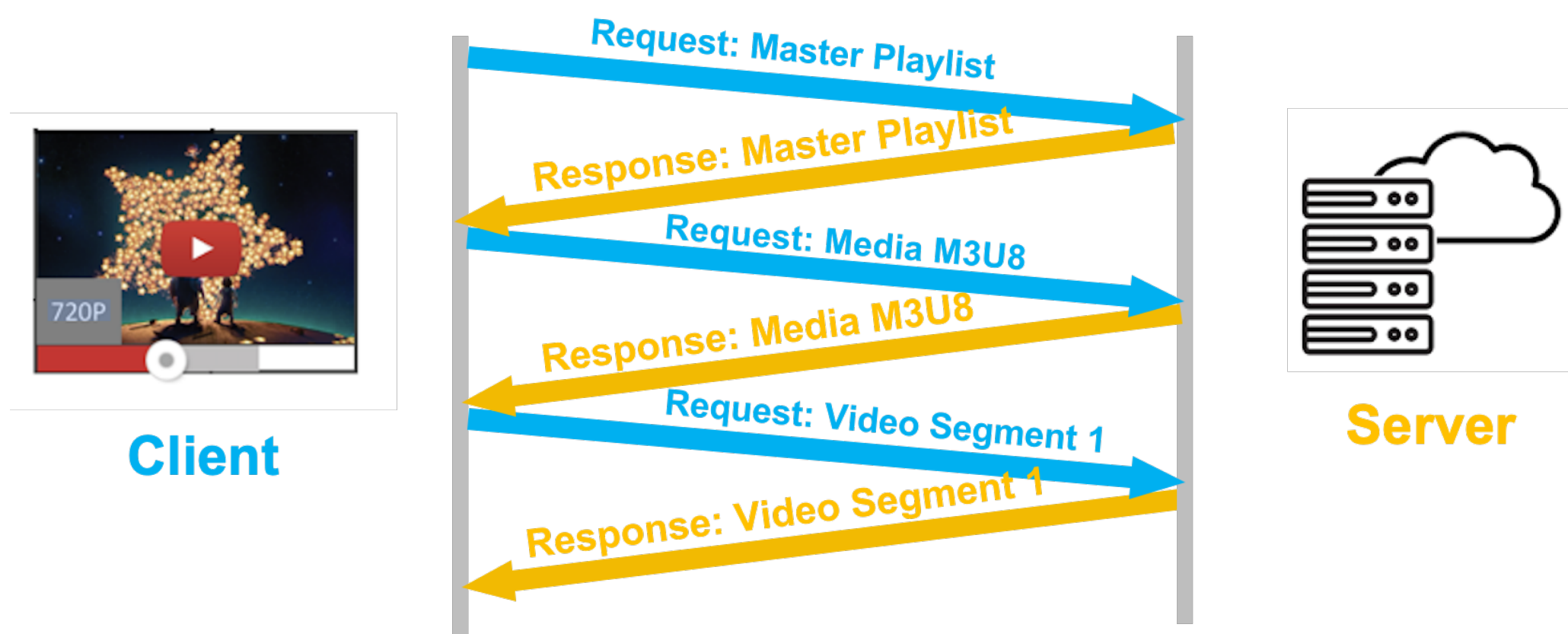

Key Contributions:

- **End-to-End Streaming System:** Developed a complete **HLS streaming pipeline**, featuring **FFmpeg-based** multi-bitrate segmentation, an **AES-128** encrypting server, a **client-side proxy** for decryption and network simulation, and an hls.js player with WebSocket for real-time **QoE feedback** and **ABR control**.
- **STARS ABR Algorithm:** Designed and implemented STARS, a novel comprehensive **rule-based** ABR. STARS leverages **stateful network analysis** and proactive strategies, demonstrating significantly **reduced rebuffering** and **superior overall QoE** compared to baseline methods across diverse simulated network environments.
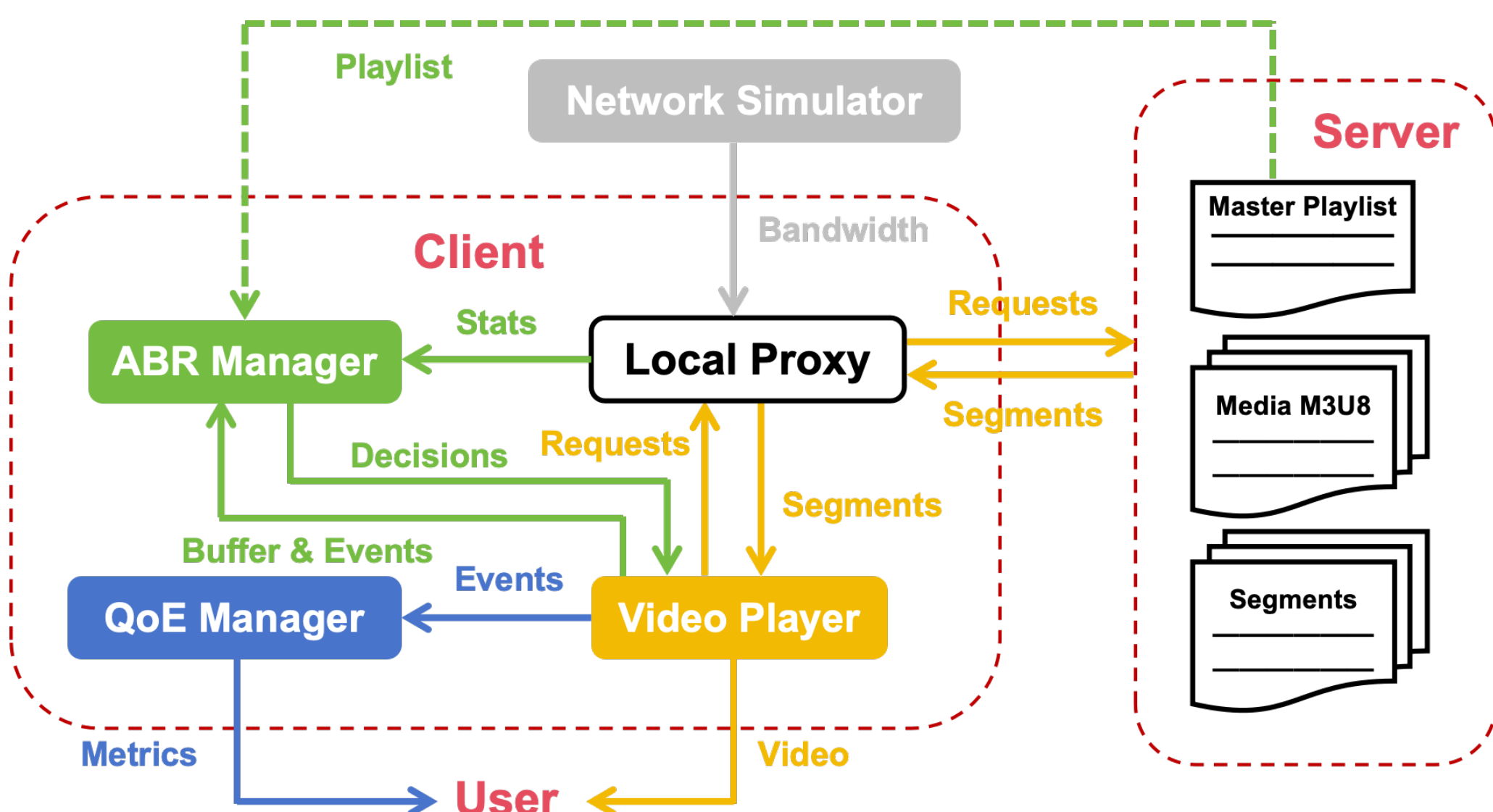

STARS ABR Algorithm & Metrics

STARS ABR Algorithm: Our STARS (STateful Adaptive Rate Selection) algorithm is a **comprehensive, rule-based** ABR designed for intelligent, proactive bitrate adaptation. Key features include:
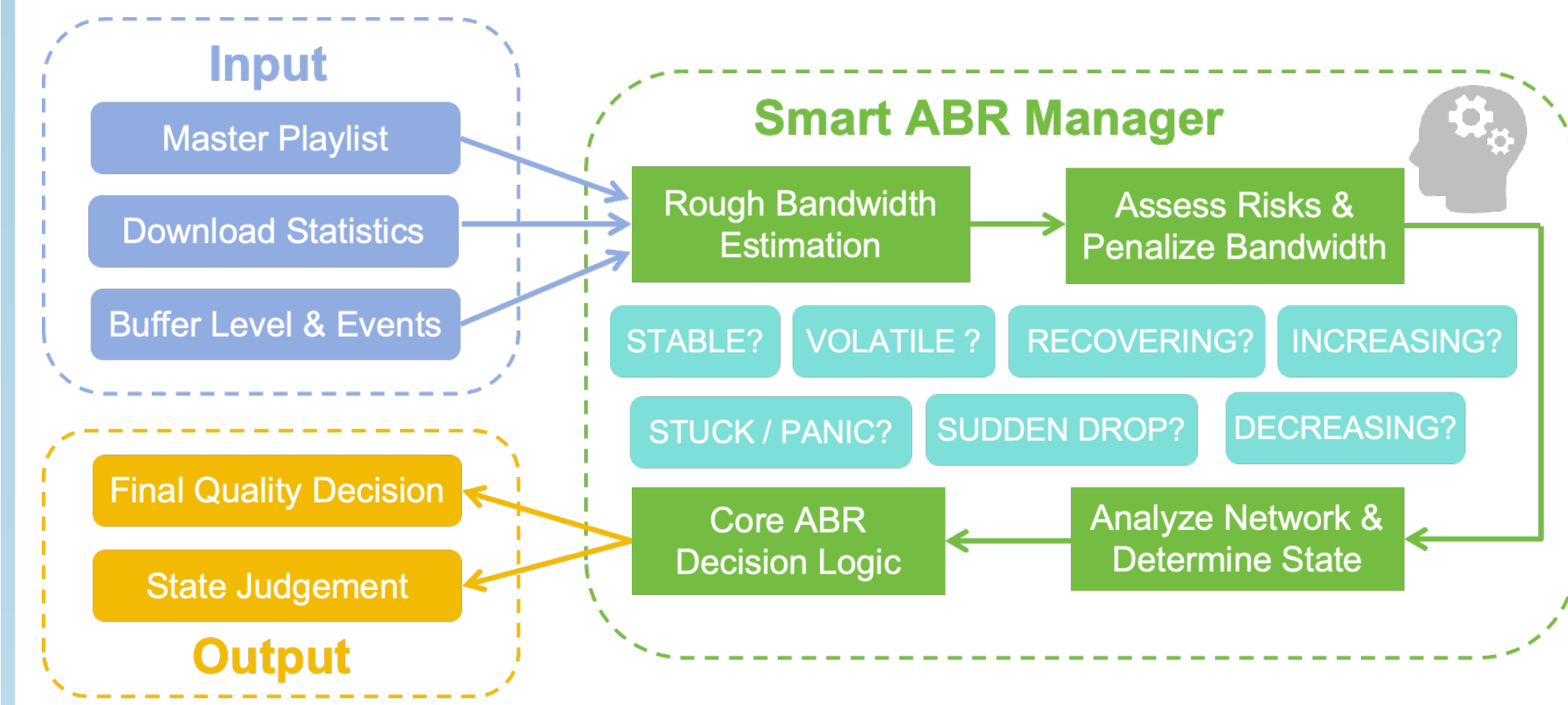
- **Stateful Network Analysis:** Dynamically interprets network indicators like EWMA/SWMA, latest segment throughput, volatility, and detected trends like "Sudden Drops".
- **Proactive Risk & Buffer Management:** Employs **dynamic penalties** for slow or STUCK segments, robust PANIC/recovery modes for severe issues, **preemptive downgrades** in high-risk situations, and accurate buffer loss estimation to ensure **stable up-switches** and minimize rebuffering.
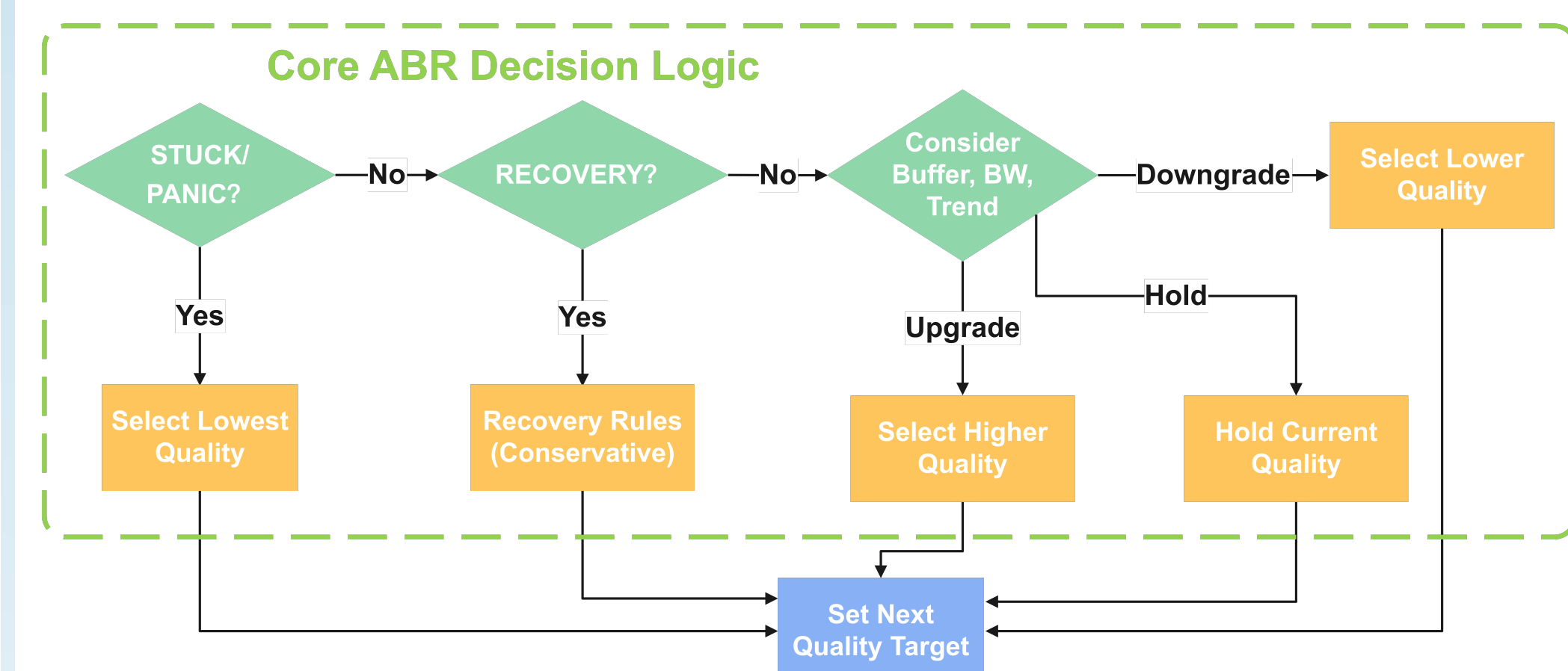
QoE & PSNR Metrics: System performance is evaluated using a Quality of Experience (**QoE**) model and Peak Signal-to-Noise Ratio (**PSNR**). Our QoE metric balances video quality utility against **penalties for rebuffering quality switches**, while PSNR assesses objective video fidelity.

$$QoE = \sum_{k=1}^{N} q(R_k) \cdot T_k - \mu \sum_{j=1}^{M} T_{stall,j}$$

$$- \tau \sum_{i=1}^{S-1} |q(R_{i+1}) - q(R_i)|_{\text{switch}} \quad (1)$$

$$PSNR = 20 \cdot \log_{10} \left(\frac{MAX_I}{\sqrt{MSE}} \right) \quad (2)$$

Experimental Evaluation & Results

Experimental Setup: STARS (Ours) and 4 baseline ABRs (SWMA, EWMA, Buffer-Only, Bandwidth-Buffer) evaluated using "Big Buck Bunny" (5 HLS quality levels, 360p-2160p) across 9 diverse, simulated network scenarios. (DQN variant explored but omitted due to time constraints).
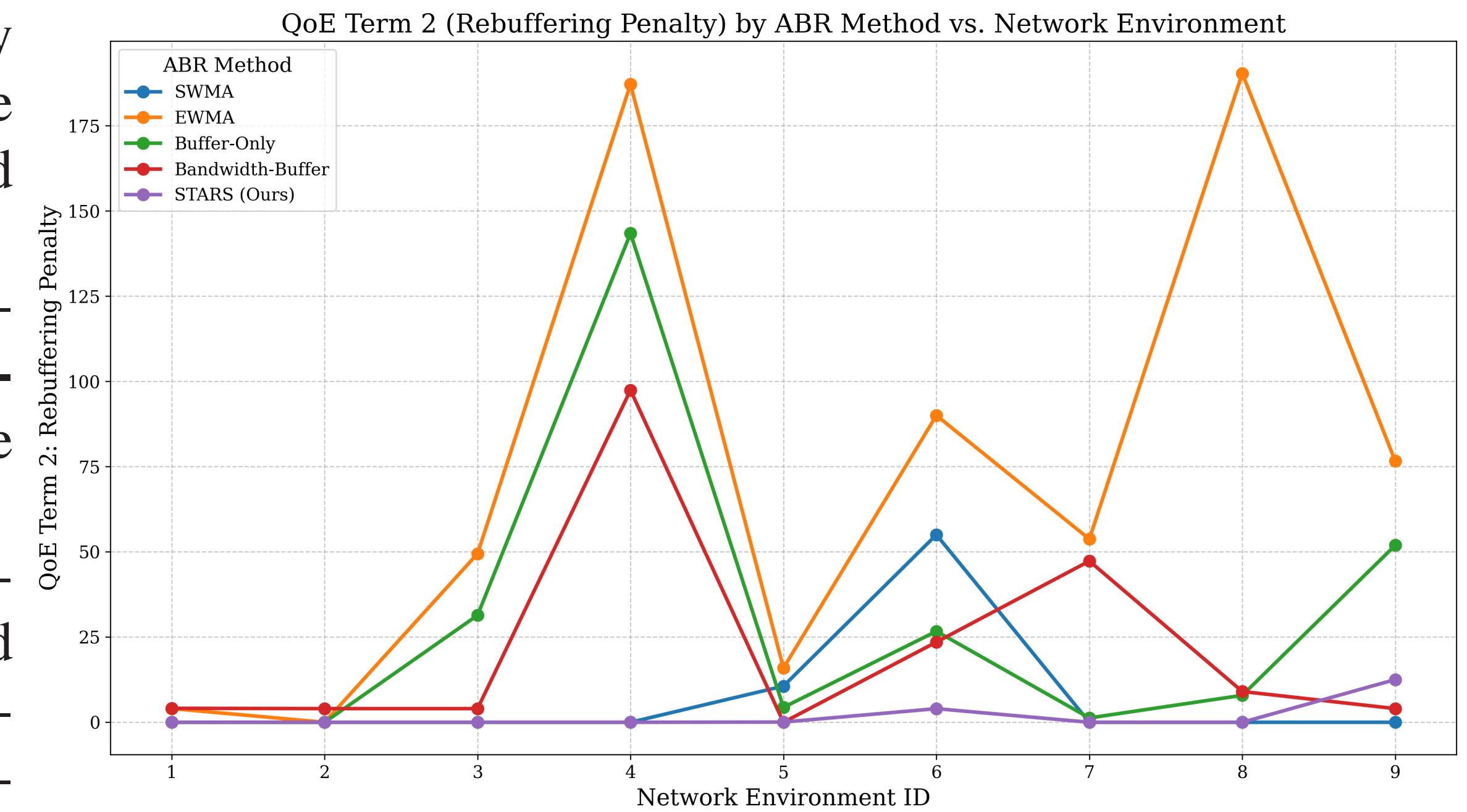
Quantitative results on different network environment:

ABR Algorithm	Stable Low (NetEnv 1)			Stable High (NetEnv 2)			Rapid Fluct. (NetEnv 3)			Drop & Recover (NetEnv 4)			Gradual Up (NetEnv 5)		
	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓
Bandwidth-Buffer	-4.10	29.58	1.03%	58.46	36.29	1.00%	51.13	35.80	1.01%	-21.74	37.91	24.34%	0.00	29.58	0.00%
Buffer-Only	0.00	29.58	0.00%	69.70	36.40	0.00%	9.57	33.89	7.84%	-44.20	40.38	35.84%	15.94	31.64	1.09%
EWMA	-4.03	29.58	1.01%	157.37	47.32	0.00%	58.85	42.57	12.35%	-52.35	46.53	46.68%	25.61	33.76	3.97%
SWMA	0.00	29.58	0.00%	0.00	29.58	0.00%	0.00	29.58	0.00%	0.00	29.58	0.00%	30.55	33.68	2.65%
STARS (Ours)	0.00	29.58	0.00%	78.56	38.53	0.00%	11.76	30.76	0.00%	2.46	29.79	0.00%	19.79	31.52	0.01%

ABR Algorithm	Gradual Down (NetEnv 6)			V-Shape (NetEnv 7)			A-Shape (NetEnv 8)			Dynamic Mix (NetEnv 9)			Average		
	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓	QoE↑	PSNR↑	REBUFF.↓
Bandwidth-Buffer	16.81	35.54	5.89%	-36.36	31.47	11.85%	28.87	34.14	2.26%	29.25	34.25	1.00%	13.59	33.84	5.38%
Buffer-Only	27.45	35.37	6.67%	36.20	33.21	0.32%	57.80	35.90	1.98%	-12.42	33.62	13.01%	17.78	34.44	7.42%
EWMA	3.92	41.39	22.45%	25.95	38.59	13.41%	-44.45	46.05	47.49%	-8.25	38.55	19.11%	18.07	40.48	18.50%
SWMA	51.95	41.96	13.75%	0.00	29.58	0.00%	0.00	29.58	0.00%	0.00	29.58	0.00%	9.17	31.41	1.82%
STARS (Ours)	37.60	33.79	1.00%	26.40	32.19	0.00%	37.62	33.30	0.00%	6.19	31.62	3.13%	24.49	32.34	0.46%

Key Findings:

- **Superior QoE & Fluency:** STARS consistently delivered the **highest average QoE scores** and the **lowest average rebuffering ratio** across all tested network conditions.
- **Balanced Performance:** While drastically minimizing stalls, STARS maintained **competitive average PSNR levels**, effectively balancing objective video quality with playback stability.
- **Robustness:** The stateful analysis and proactive risk management inherent in STARS proved **highly effective**, especially in dynamic and challenging network environments where other methods struggled.

QoE Term 2 (Rebuffering Penalty) by ABR Method vs. Network Environment

Visualization of mean QoE:

Mean Final QoE Score by ABR Method

Visualization of mean PSNR:

Mean PSNR (dB) by ABR Method