MetaPipe: Budget-Constrained Multi-Stage Time-Series Routing

Input Time Series

$\mathbf{x}_t \in \mathbb{R}^{C \times t}$

Horizon set

① TCAR: Temporal Context-Aware Routing

79-D Feature Extraction

- Statistical (33)
- Temporal (22)
- Spectral (19)
- Meta (5)
- DTW Kernel
- FFT Features

ϕ (79-D)

Domain Adaptation

② MAP: Multi-Horizon Adaptive Policy

Multi-Horizon Q-Learning

- $Q_{MH}(s,a) = \sum_h w_h Q_h(s,a)$
- Adaptive Weighting
- TD Learning Updates

Q_{MH}

③ BCPR: Budget-Constrained Pareto

Lagrangian Primal-Dual

- $\mathcal{L}(\pi, \lambda, \mu)$
- Cost constraint: $C \le B_c$
- Latency constraint: $L \le B_l$

π^*

④ UQE: Uncertainty

Conformal Prediction

- $P(y \in C_\alpha) \ge 1 - \alpha$
- Coverage Guarantee
- Adaptive Escalation

Routing Decision

⑤ CPTL: Cross-Pipeline Transfer

Meta-Learning (MAML-inspired)

- Zero-shot Transfer
- Few-shot Fine-tuning

4-Stage Time-Series Pipeline

Action Space: $\mathcal{A} = \mathcal{A}_1 \times \mathcal{A}_2 \times \mathcal{A}_3 \times \mathcal{A}_4$ (625 configs)

Stage 1 Retrieval
- DTW
- Matrix Profile
- KNN

Stage 2 Forecasting
- ARIMA
- LSTM
- Time-LLM

Stage 3 Anomaly Detection
- Z-score
- IsolationF
- AutoEnc

Stage 4 Validation
- Conformal
- Ensemble
- Bayes

Key Innovations

- ✓ 79-D temporal features
- ✓ Multi-horizon optimization
- ✓ Hard budget constraints
- ✓ Distribution-free guarantees
- ✓ Zero-shot transfer

Output

Predictions: $\hat{y}^{(h)}$ for all $h \in \mathcal{H}$

Quality Metrics:
- SMAPE, MASE, RMSE
- Multi-horizon accuracy

Cost Metrics:
- Total cost: $C(\mathbf{a})$
- Budget compliance

Latency Metrics:
- End-to-end: $L(\mathbf{a})$
- Real-time feasibility

Uncertainty:
- Confidence intervals: $C_\alpha(x)$

Training: Offline meta-learning across 30+ datasets

Inference: Real-time routing with sublinear complexity