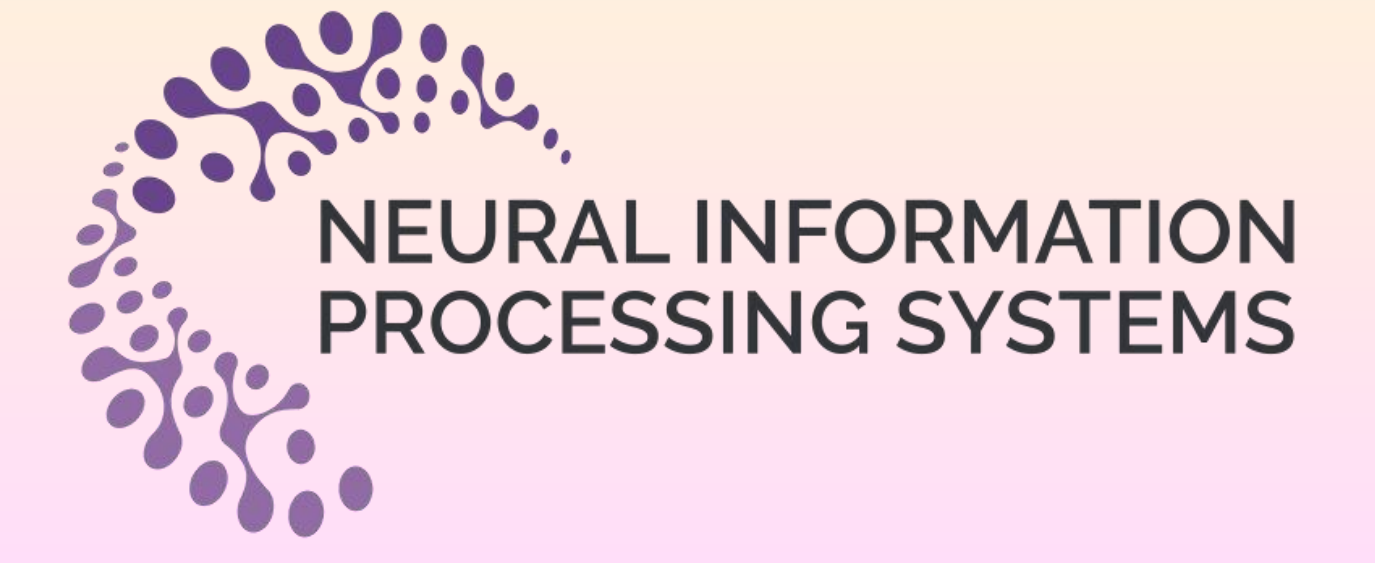


STRAP: Spatio-Temporal Pattern Retrieval for Out-of-Distribution Generalization

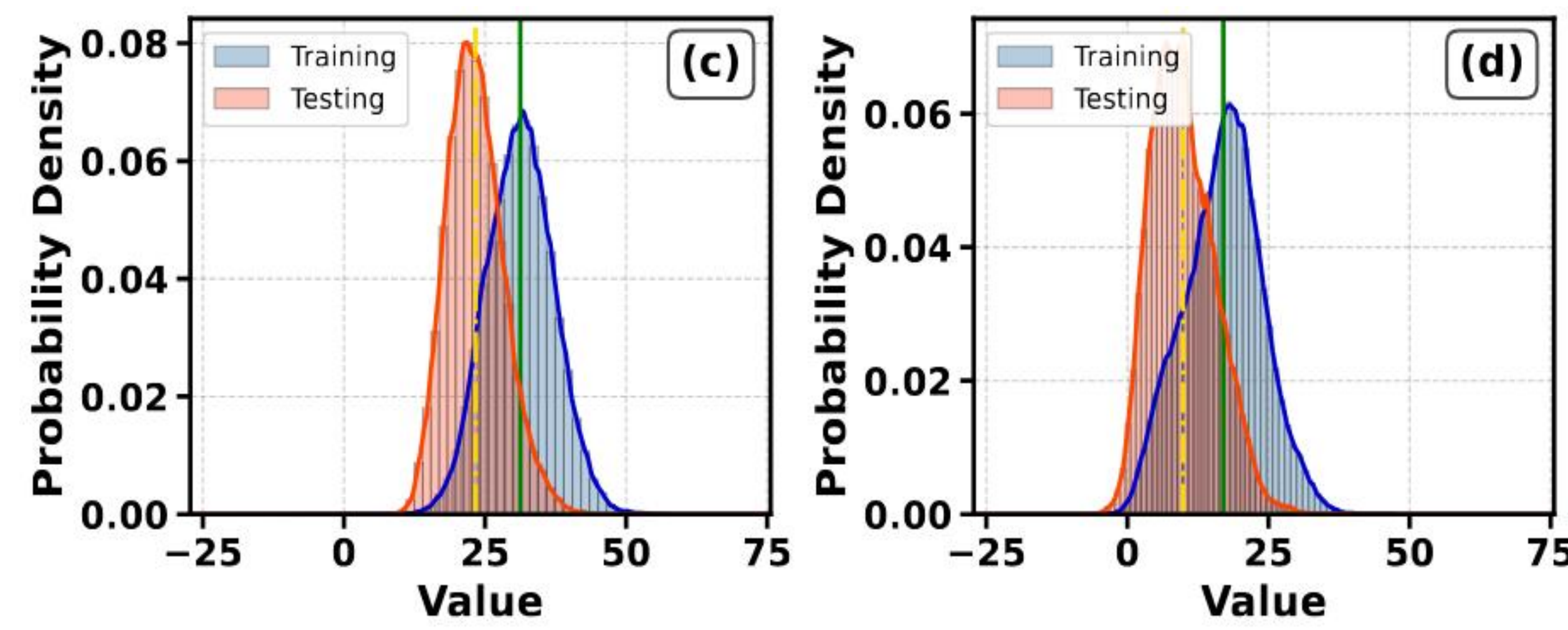
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Motivation

- Distribution shifts in spatio-temporal graphs mean historical data only partially helps; some becomes noise or harmful.
- Core challenge: identify which historical components provide maximal information gain under complex shifts.
- Instead of storing patterns implicitly in parameters, explicitly store key, similar historical patterns.
- Explicit external storage preserves more history without parameter updates.



Challenges

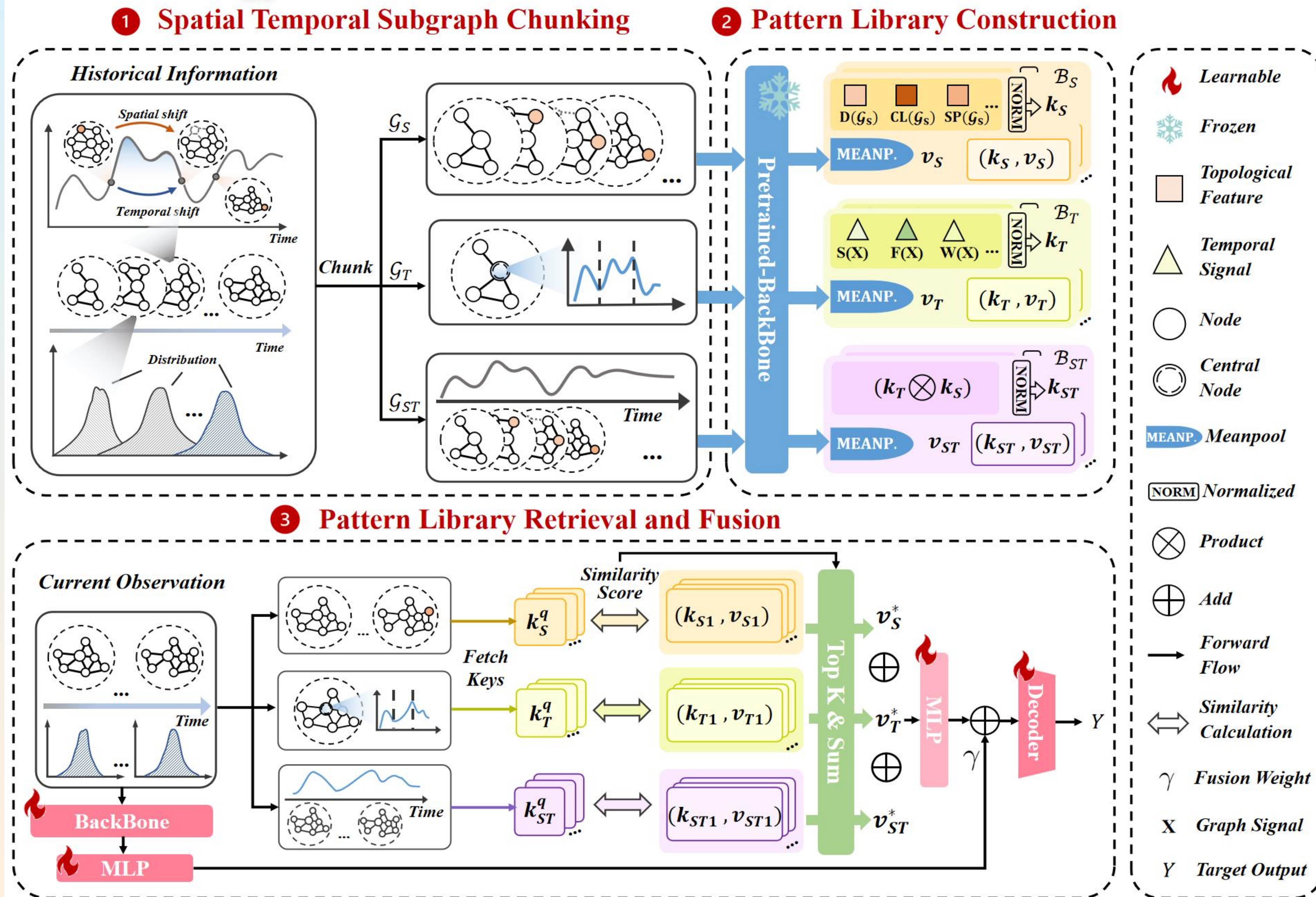
C1. How to Identify and Store Contributive Patterns?

Methods fixate on spatial cues or static graphs, missing richer histories; parameter memory is limited (esp. in STOOD). Key: select high-information-gain spatio-temporal patterns and store them efficiently for current prediction.

C2. How to Balance Historical Patterns with Current Observations?

Weak similarity/retrieval hinders matching; over-reliance causes overfitting and blurs prediction vs. retrieval. Need mechanisms that balance historical pattern use with current data for flexible, robust spatio-temporal prediction.

Methodology



- 3D key-value pattern library:** decouple indexing vs. semantics, externalize and efficiently store contributive patterns (*for C1*)
- Similarity-based multi-library retrieval:** top-K, softmax-weighted aggregation across spatial/temporal/st-spatial libraries to avoid noisy replay (*bridging C1→C2*)
- Adaptive knowledge fusion:** dual-encoder + γ -weighted convex blend with knowledge-balancing objective (*for C2*)

Experiments

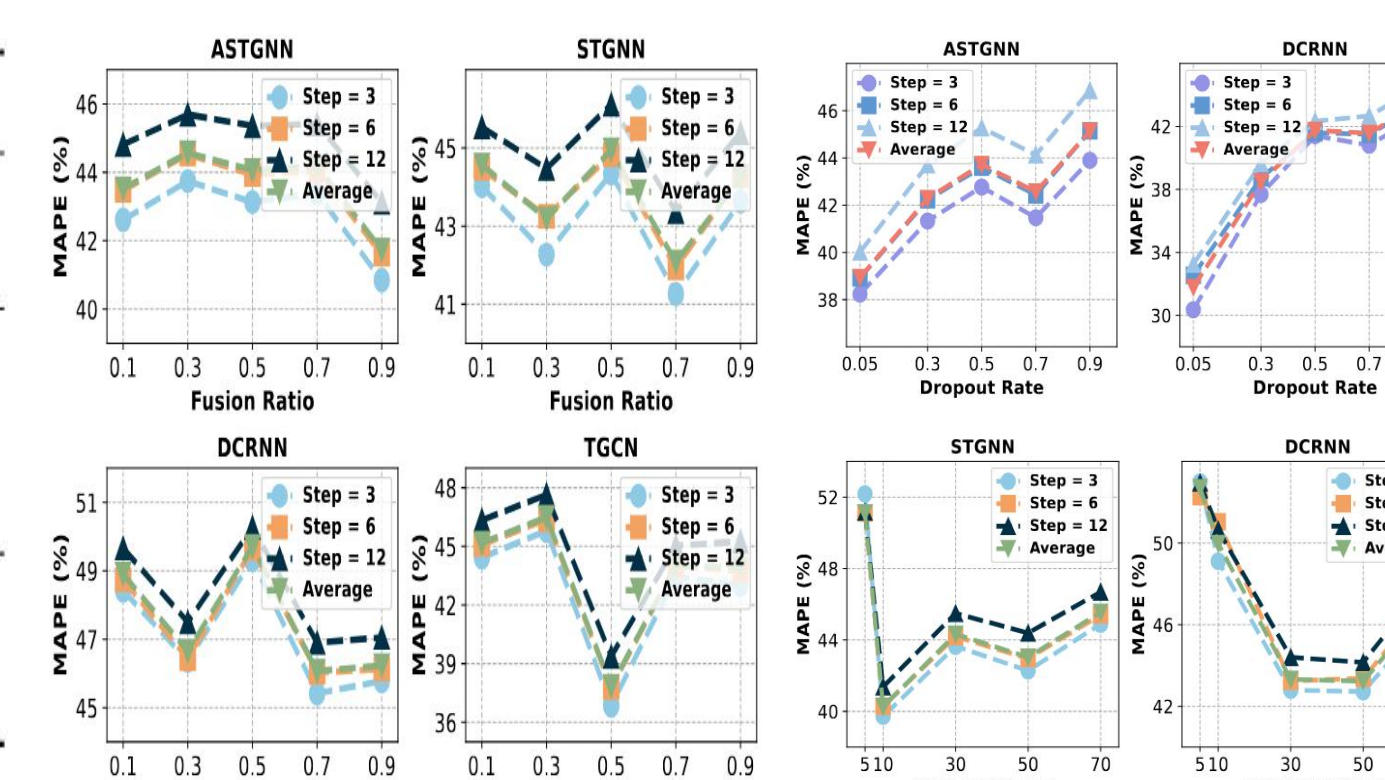
Datasets

Dataset	Domain	Time Range	Period	Node Evolution	Frequency	Frames
Air-Stream	Weather	01/01/2016-12/31/2019	4	1087 → 1115 → 1154 → 1193 → 1202 655 → 713 → 786	1 hour	34,065
PEMS-Stream	Traffic	07/10/2011-09/08/2017	7	→ 822 → 834 → 850 → 871	5 min	61,992
Energy-Stream	Energy	Unknown (245 days)	4	103 → 113 → 122 → 134	10 min	34,560

Few-shot Performance

Data Availability		50% Missing Data					30% Missing Data					All Data				
Category	Method	Metric	3	6	12	Avg.	3	6	12	Avg.	3	6	12	Avg.	3	Avg.
Backbone	Pretrain	MAE	7.16±0.12	7.16±0.11	7.15±0.09	7.16±0.11	6.23±0.08	6.17±0.07	6.21±0.06	6.18±0.07	8.94±0.15	8.92±0.14	8.93±0.13	8.93±0.14		
		RMSE	7.28±0.13	7.31±0.12	7.37±0.10	7.32±0.12	6.41±0.09	6.40±0.08	6.53±0.07	6.41±0.08	9.12±0.16	9.15±0.15	9.18±0.14	9.15±0.15		
		MAPE (%)	92.44±2.18	93.38±1.95	94.65±1.82	93.36±1.98	75.08±1.85	75.47±1.72	76.77±1.68	75.60±1.75	118.25±3.42	119.15±3.28	120.38±3.15	119.26±3.28		
	Retrain	MAE	6.91±0.08	6.89±0.07	6.86±0.06	6.89±0.07	6.35±0.05	6.28±0.04	6.27±0.03	6.27±0.04	5.68±0.12	5.50±0.08	5.48±0.06	5.55±0.09		
		RMSE	7.05±0.09	7.06±0.08	7.10±0.07	7.06±0.08	6.55±0.06	6.52±0.05	6.61±0.04	6.53±0.05	5.83±0.14	5.72±0.04	5.80±0.02	5.77±0.06		
		MAPE (%)	89.03±1.95	89.91±1.82	90.96±1.75	89.78±1.84	70.70±1.25	71.28±1.18	72.51±1.12	71.32±1.18	53.70±2.15	53.67±1.98	55.72±1.85	54.04±1.99		
Architecture-based	GraphPro	MAE	6.94±0.15	6.92±0.12	6.93±0.11	6.93±0.13	6.07±0.08	5.96±0.06	6.00±0.05	5.97±0.06	5.68±0.14	5.50±0.06	5.48±0.06	5.55±0.06		
		RMSE	7.04±0.16	7.06±0.13	7.14±0.12	7.07±0.14	6.28±0.09	6.20±0.07	6.34±0.06	6.23±0.07	5.83±0.14	5.72±0.04	5.80±0.02	5.77±0.06		
		MAPE (%)	91.25±2.85	92.12±2.65	93.69±2.48	92.18±2.66	74.31±1.95	74.73±1.82	76.14±1.75	74.86±1.84	53.70±2.22	53.67±2.32	55.17±2.35	54.04±2.34		
	ST-Adapter	MAE	7.02±0.18	7.01±0.16	7.02±0.15	7.03±0.16	6.19±0.12	6.16±0.10	6.22±0.09	6.16±0.10	5.47±0.06	5.37±0.12	5.35±0.09	5.39±0.09		
		RMSE	7.24±0.19	7.28±0.17	7.38±0.16	7.30±0.17	6.48±0.13	6.47±0.11	6.61±0.10	6.48±0.11	5.63±0.06	5.59±0.12	5.68±0.08	5.62±0.10		
		MAPE (%)	98.47±3.25	99.12±3.08	99.98±2.95	99.09±3.09	76.15±2.15	76.64±2.05	77.96±1.98	76.74±2.06	51.17±2.42	51.59±2.17	52.87±2.25	51.78±2.20		
Regularization-based	EWC	MAE	6.91±0.12	6.89±0.10	6.86±0.09	6.89±0.10	6.35±0.08	6.28±0.06	6.27±0.05	6.27±0.06	5.47±0.09	5.37±0.14	5.37±0.16	5.40±0.10		
		RMSE	7.05±0.13	7.06±0.11	7.10±0.10	7.06±0.11	6.55±0.09	6.52±0.07	6.61±0.06	6.53±0.07	5.62±0.10	5.57±0.11	5.67±0.12	5.61±0.08		
		MAPE (%)	89.03±2.25	89.91±2.12	90.96±2.05	89.78±2.14	70.70±1.85	71.28±1.75	72.51±1.68	71.32±1.76	51.78±0.53	52.05±0.94	53.43±0.92	52.32±0.78		
	Replay	MAE	7.16±0.15	7.16±0.14	7.15±0.13	7.16±0.14	6.23±0.10	6.17±0.08	6.21±0.07	6.18±0.08	5.52±0.07	5.42±0.21	5.46±0.16			
		RMSE	7.28±0.16	7.31±0.15	7.37±0.14	7.32±0.15	6.41±0.11	6.40±0.09	6.53±0.08	6.41±0.09	5.67±0.06	5.63±0.18	5.72±0.18	5.67±0.14		
		MAPE (%)	92.44±2.95	93.38±2.82	94.65±2.75	93.36±2.84	75.08±2.05	75.47±1.95	76.77±1.88	75.60±1.96	52.54±1.52	52.95±1.58	54.38±1.79	53.19±1.62		
Retrieval-based	STRAP	MAE	6.31±0.08	6.29±0.07	6.28±0.06	6.29±0.07	5.74±0.05	5.64±0.04	5.66±0.03	5.77±0.04	4.83±0.17	4.84±0.18	4.88±0.17	4.85±0.18		
		RMSE	6.44±0.09	6.46±0.08	6.53±0.07	6.47±0.08	6.10±0.06	6.01±0.05	6.11±0.04	6.14±0.05	4.95±0.18	5.01±0.19	5.15±0.17	5.03±0.18		
		MAPE (%)	78.28±1.85	78.93±1.75	79.98±1.68	78.92±1.76	66.53±1.25	67.02±1.18	68.36±1.12	67.42±1.18	42.18±1.64	43.02±1.77	44.30±1.55	43.11±1.72		
	Replay	MAE	7.16±0.15	7.16±0.14	7.15±0.13	7.16±0.14	6.23±0.10	6.17±0.08	6.21±0.07	6.18±0.08	5.52±0.07	5.42±0.21	5.46±0.16			
		RMSE	7.28±0.16	7.31±0.15	7.37±0.14	7.32±0.15	6.41±0.11	6.40±0.09	6.53±0.08	6.41±0.09	5.67±0.06	5.63±0.18	5.72±0.18	5.67±0.14		
		MAPE (%)	92.44±2.95	93.38±2.82	94.65±2.75	93.36±2.84	75.08±2.05	75.47±1.95	76.77±1.88	75.60±1.96	52.54±1.52	52.95±1.58	54.38±1.79	53.19±1.62		

Hyper-parameter Study



Main Results

Datasets		Air-Stream					PEMS-Stream					Energy-Stream				
Category	Method	Metric	3	6	12	Avg.	3	6	12	Avg.	3	6	12	Avg.		
Backbone	Pretrain	MAE	18.96±2.55	21.87±2.15	25.02±1.59	21.62±2.15	14.06±0.18	15.14±0.19	17.44±0.24	15.32±0.20	10.71±0.05	10.74±0.09	10.76±0.10	10.73±0.08		
		RMSE	30.11±3.81	35.21±3.31	40.26±2.62	34.58±3.33	21.86±0.23	23.97±0.27	28.10±0.36	24.24±0.27	10.86±0.06	10.98±0.15	11.06±0.15	10.95±0.11		
		MAPE (%)	22.88±2.18	27.04±1.59	32.01±0.95	26.86±1.63	33.01±2.80	39.40±0.54	44.04±0.05	32.28±2.48	101.42±5.41	177.49±8.28	178.50±8.52	176.83±7.31		
	Retrain	MAE	19.16±1.42	21.90±1.21	25.02±0.97	21.73±1.23	12.93±0.08	14.04±0.05	16.35±0.05	14.22±0.05	5.50±0.05	5.42±0.17	5.42±0.17	5.45±0.12		
		RMSE	30.13±1.95	34.88±1.60	39.89±1.30	34.42±1.67	20.86±0.09	22.94±0.06	26.98±0.11	23.19±0.08	5.66±0.05	5.64±0.13	5.74±0.15	5.67±0.09		
		MAPE (%)	24.98±2.74	28.69±2.32	33.16±1.71	28.53±2.27	17.75±0.51	20.12±0.39	23.39±0.39	20.44±0.42	52.22±0.18	52.72±0.45	53.82±0.55	52.80±0.24		
	TrafficStream	MAE	18.54±0.53	21.49±0.45	24.81±0.41	21.29±0.47	12.94±0.03	14.07±0.06	16.34±0.08	14.23±0.05	5.50±0.05	5.40±0.19	5.40±0.20	5.44±0.14		
		RMSE	28.65±0.70	33.98±0.59	39.40±0.54	33.37±0.63	20.83±0.04	22.92±0.08	26.86±0.11	23.15±0.07	5.65±0.06	5.62±0.14	5.70±0.15	5.65±0.09		
		MAPE (%)	23.87±0.21	27.80±0.41	32.81±0.68	27.75±0.42	17.89±0.70	19.49±0.73	23.13±0.73	19.83±0.70	50.14±1.24	50.48±1.65	51.84±1.62	50.72±1.47		
	Architecture-based	ST-LoRA	MAE	18.54±0.69	21.45±0.66	24.65±0.54	21.22±0.63	12.76±0.05	13.88±0.06	16.10±0.08	14.03±0.05	5.44±0.01	5.34±0.14	5.34±0.15	5.38±0.09	
			RMSE	28.94±1.16	34.19±1.12	39.40±0.97	33.54±1.09	20.62±0.08	22.68±0.11	26.54±0.14	22.89±0.09	5.59±0.00	5.55±0.12	5.65±0.13	5.59±0.08	
			MAPE (%)	23.04±0.34	26.98±0.31	31.90±0.17	26.89±0.28	17.15±0.24	18.59±0.29	21.97±0.41	18.91±0.29	52.60±1.70	53.08±1.45	54.70±1.35	53.34±1.54	
STKEC		MAE	18.87±0.44	21.74±0.35	24.94±0.17	21.52±0.34	12.96±0.13	14.07±0.11	16.33±0.07	14.24±0.11	5.56±0.12	5.57±0.07	5.55±0.08	5.55±0.09		
		RMSE	29.92±0.58	34.80±0.46	39.81±0.22	34.25±0.41	20.85±0.15	22.89±0.12	26.80±0.09	23.13±0.12	5.73±0.10	5.78±0.06	5.87±0.06	5.78±0.08		
		MAPE (%)	24.12±0.24	27.91±0.24	32.70±0.14	27.83±0.19	18.73±0.46	20.07±0.43	23.30±0.31	20.39±0.33	53.13±0.16	53.74±0.31	55.01±0.47	53.81±0.30		
EAC		MAE	18.59±0.38	21.44±0.30	24.63±0.24	21.23±0.31	12.95±0.31	13.85±0.42	15.63±0.72	13.97±0.46	5.20±0.21	5.25±0.23	5.29±0.19	5.24±0.20		
		RMSE	28.39±0.37	33.60±0.24	38.85±0.16	32.98±0.25	20.65±0.03	22.63±0.62	25.40±1.16	22.48±0.69	5.45±0.18	5.58±0.18	5.72±0.18	5.57±0.16		
		MAPE (%)	23.47±0.47	27.24±0.43	32.07±0.45	27.19±0.45	19.47±0.29	20.39±0.31	22.50±0.24	20.59±0.25	56.19±5.64	57.66±5.09	58.56±5.34	57.38±5.31		
Regularization-based		ST-Adapter	MAE	19.11±0.44	21.94±0.61	25.27±0.77	21.77±0.59	12.71±0.05	13.80±0.05	15.97±0.09	13.95±0.06	5.47±0.06	5.37±0.12	5.35±0.09	5.39±0.09	
			RMSE	29.14±0.61	34.37±0.84	38.86±0.13	33.81±0.81	20.55±0.06	22.55±0.07	26.31±0.17	22.76±0.08	5.63±0.06	5.59±0.02	5.68±0.08	5.62±0.10	
			MAPE (%)	23.65±0.28	27.27±0.29	31.90±0.36	27.22±0.26	17.58±0.45	18.78±0.31	21.71±0.34	19.10±0.35	51.17±2.42	51.59±2.17	52.87±2.25	51.78±2.20	
	GraphPro	MAE	18.92±1.13	21.68±0.86	24.96±0.71	21.53±0.92	12.77±0.07	13.91±0.09	16.20±0.15	14.08±0.10	5.68±0.14	5.50±0.06	5.48±0.06	5.55±0.06		
		RMSE	29.68±1.42	34.53±0.98	39.73±0.74	34.04±1.09	20.63±0.09	22.74±0.13	26.68±0.20	22.96±0.13	5.83±0.14	5.72±0.04	5.80±0.02	5.77±0.06		
		MAPE (%)	23.56±1.34	27.44±1.06	32.36±0.78	27.36±1.07	17.63±1.08	19.23±1.14	23.04±1.16	19.63±1.12	53.70±5.22	53.67±5.32	55.17±5.23	54.45±5.34		
	PECPM	MAE	18.44±0.18	21.36±0.14	24.66±0.10	21.17±0.15	12.75±0.02	13.88±0.03	16.11±0.06	14.03±0.03	5.46±0.04	5.46±0.04	5.48±0.02	5.47±0.03		
		RMSE	28.74±0.22	33.89±0.13	39.16±0.09	33.33±0.16	20.71±0.09	22.70±0.09	26.56±0.15	22.91±0.09	5.59±0.03	5.63±0.03	5.74±0.02	5.65±0.03		
		MAPE (%)	23.85±0.85	27.73±0.80	32.61±0.71	27.65±0.79	17.63±0.77	19.24±0.80	22.92±0.85	19.60±0.80	53.18±2.14	53.81±1.93	55.31±1.98	54.01±2.04		
	EWC	MAE	18.21±0.44	21.19±0.37	24.59±0.32	21.00±0.38	13.05±0.12	14.26±0.11	16.72±0.10	14.45±0.11	5.47±0.09	5.37±0.14	5.37±0.16	5.40±0.10		
		RMSE	28.50±0.39	33.85±0.39	39.38±0.40	33.26±0.39	21.14±0.18	23.42±0.19	27.75±0.22	23.69±0.20	5.62±0.10	5.57±0.11	5.67±0.12	5.61±0.08		
		MAPE (%)	23.04±0.77	27.07±0.55	32.18±0.43	27.01±0.59	17.32±0.34	18.81±0.49	22.19±0.71	19.13±0.48	51.78±0.53	52.05±0.94	53.43±0.92	52.32±0.78		
Replay-based	Replay	MAE	17.95 ±0.27	21.06±0.32	24.47±0.35	20.82±0.31	12.96±0.14	14.09±0.04	16.38±0.07	14.27±0.05	5.52±0.07	5.42±0.21	5.42±0.21	5.46±0.16		
		RMSE	28.14±0.46	33.57±0.45	39.00±0.45	32.92±0.45	20.84±0.06	22.93±0.06	26.94±0.10	23.19±0.07	5.67±0.06	5.63±0.18	5.72±0.18	5.67±0.14		
		MAPE (%)	22.61 ±0.35	26.91±0.56	32.19±0.68	26.79±0.56	18.19±0.08	19.52±0.11	22.66±0.26	19.82±0.13	52.54±1.52	52.95±0.58	54.38±1.79	53.19±1.62		
Retrieval-based	StrAP	MAE	18.04±0.52	20.49 ±0.41	23.45 ±0.33	20.37 ±0.45	12.19 ±0.18	13.13 ±0.15	15.20 ±0.17	13.31 ±0.17	4.83 ±0.17	4.84 ±0.18	4.88 ±0.17	4.85 ±0.18		
		RMSE	26.65 ±0.45	30.87 ±0.39	35.56 ±0.34	30.55 ±0.43	18.54 ±0.25	20.18 ±0.21	23.67 ±0.26	20.46 ±0.23	4.95 ±0.18	4.91 ±0.19	5.15 ±0.17	5.03 ±0.18		
		MAPE (%)	23.72 ±0.59	26.78 ±0.43	30.73 ±0.37	26.44 ±0.43	16.55 ±0.55	17.70 ±0.69	20.57 ±0.97	18.02 ±0.72	42.18 ±0.64	43.02 ±0.77	44.30 ±1.55	43.41 ±1.72		