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# TSNet: a foundation model for wireless network status prediction in digital twins

**Key words:** Digital twin; Communication network; Foundation model; Network status prediction

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# Motivation

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- ❑ A **digital twin network (DTN)** is a virtual representation of a physical communication network.
- ❑ Network status prediction is a basic DTN capability.
- ❑ In wireless networks, there are many kinds of measurements that characterize the network status, such as radio resource utilization and user equipment (UE) throughput. Network status prediction is fundamentally a problem of **time-series forecasting**.
- ❑ In this paper, we want to propose a **general framework** for network status prediction in DTNs, to handle numerous and various network measurements.

# Related works

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In the literature, many efforts have been devoted to time-series prediction.

□ Traditional statistical methods: ARIMA, Holt-winter

- make strong assumptions on data distribution

□ Traditional machine learning methods: using classical regression algorithms, for example random forest and XGBoost

- require engineers to design effective features carefully to achieve high accuracy

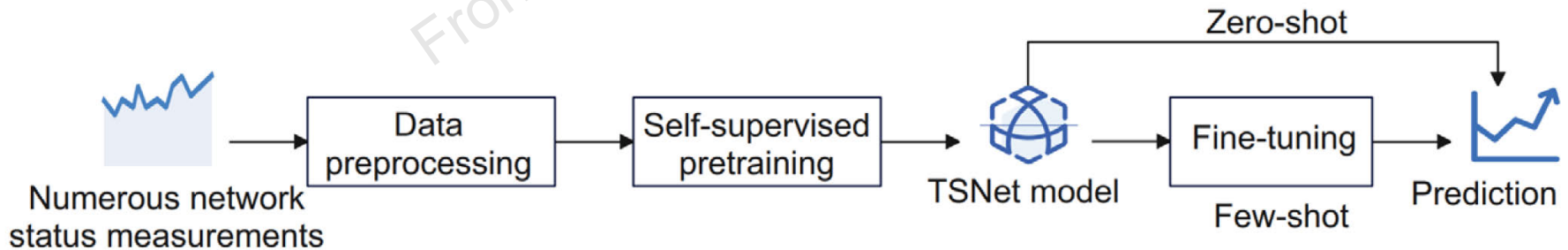
□ Deep neural networks: RNN, LSTM, CNN, Transformers

□ Foundation models: TimesNet, GPT4TS, LLM4TS, TimesFM

- directly apply CV/NLP foundation model to time series
- pure time-series pretrained model

# Framework

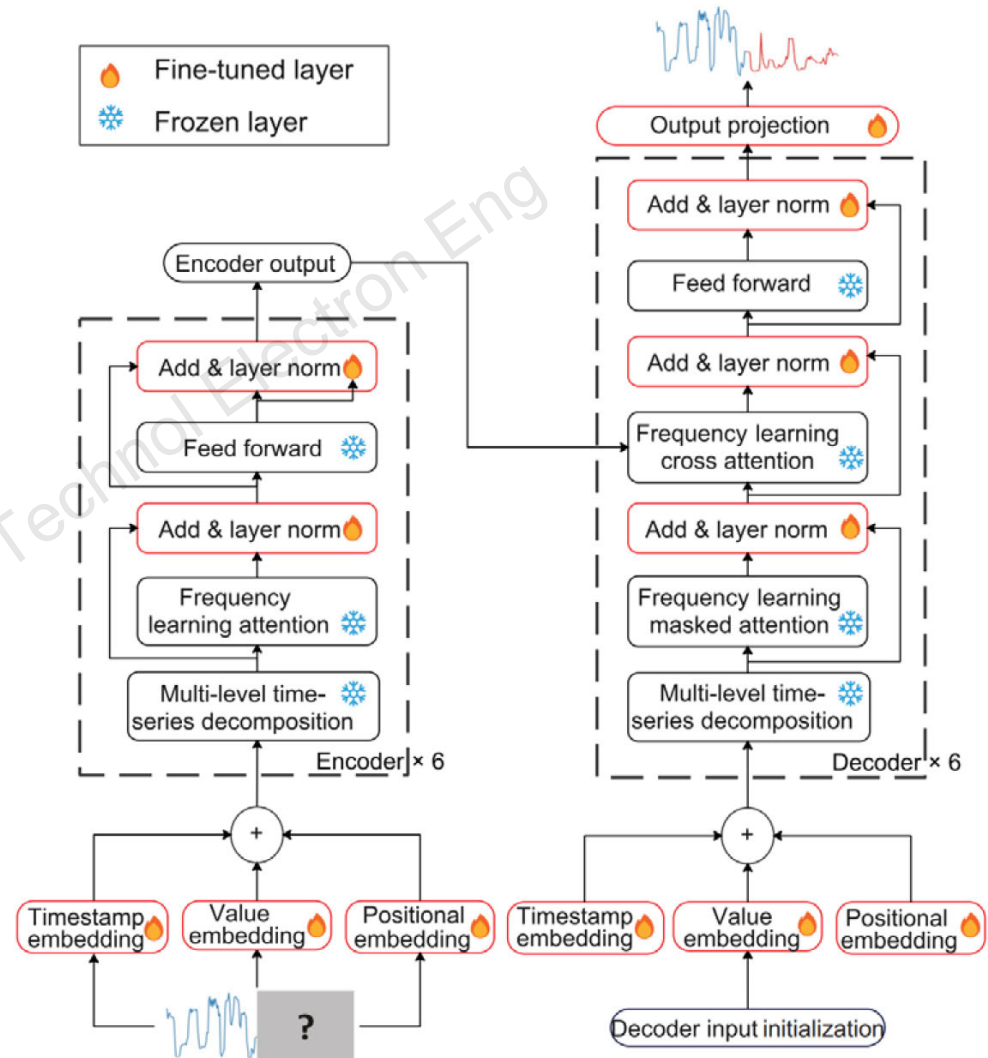
- Data preprocessing: filter low-quality data and standardize the data
  - Data quality measurement: completeness and variation
  - Data normalization
- Pretraining
  - A novel network architecture for TSNet with 0.1 billion parameters
  - A self-supervised manner using a prediction task with an MSE loss function
- Prediction
  - Zero-shot
  - Few-shot: fine-tuning to freeze the majority of parameters



Pipeline of TSNet

# Model architecture

- ❑ **Input embedding:** positional embedding and timestamp embedding
- ❑ **Channel independence:** multivariate time-series data are processed independently
- ❑ **Time-series decomposition:** separate the original time series and hidden states into distinct seasonal and trend components.
- ❑ **Frequency learning attention:** implement multi-head attention in the frequency domain to capture implicit features.



# Experiments

TSNet outperforms baseline models in most cases regarding MSE and MAE.

Cell	Metric	TSNet (zero-shot)		LSTM		Nbeats		TFT		NHITS		TSNet (fine-tuned)	
		MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE	MSE	MAE
1	PRB.DL	0.0117	<b>0.0792</b>	0.0215	0.1073	<b>0.0100</b>	0.0811	0.0175	0.0986	0.0118	0.0845	<i>0.0084</i>	<i>0.0701</i>
	PRB.UL	0.0171	0.1038	0.0211	0.1078	<b>0.0132</b>	<b>0.0895</b>	0.0176	0.1057	0.0157	0.0969	<i>0.0142</i>	<i>0.0964</i>
	Traffic.DL	<b>0.0118</b>	<b>0.0782</b>	0.0205	0.1021	0.0133	0.0847	0.0413	0.1664	0.0155	0.0919	<i>0.0091</i>	<i>0.0726</i>
	Traffic.UL	<b>0.0215</b>	0.1065	0.0292	0.1172	0.0223	0.1062	0.0248	0.1201	0.0219	<b>0.1019</b>	<i>0.0155</i>	<i>0.0883</i>
	Num.user	0.0072	0.0634	0.0128	0.0822	<b>0.0036</b>	<b>0.0454</b>	0.0144	0.0854	0.0039	0.0488	<i>0.0042</i>	<i>0.0487</i>
	Thrp.DL	<b>0.0192</b>	0.1062	0.0265	0.1217	0.0203	<b>0.1010</b>	0.0389	0.1459	0.0241	0.1105	<i>0.0106</i>	<i>0.0851</i>
	Thrp.UL	<b>0.0313</b>	<b>0.1339</b>	0.0514	0.1796	0.0352	0.1482	0.0490	0.1797	0.0452	0.1640	<i>0.0210</i>	<i>0.1184</i>
	RRC.connect	0.0072	0.0614	0.0441	0.1782	0.0041	0.0505	0.0616	0.2093	<b>0.0039</b>	<b>0.0464</b>	<i>0.0049</i>	<i>0.0497</i>
2	PRB.DL	<b>0.0300</b>	<b>0.1143</b>	0.0579	0.1731	0.0428	0.1426	0.0490	0.1615	0.0425	0.1424	<i>0.0141</i>	<i>0.0892</i>
	PRB.UL	<b>0.0346</b>	<b>0.1255</b>	0.1169	0.2846	0.0756	0.2153	0.0871	0.2416	0.0979	0.2586	<i>0.0156</i>	<i>0.0884</i>
	Traffic.DL	<b>0.0228</b>	<b>0.1050</b>	0.0398	0.1427	0.0646	0.1974	0.0372	0.1416	0.0296	0.1227	<i>0.0134</i>	<i>0.0841</i>
	Traffic.UL	<b>0.0505</b>	<b>0.1041</b>	0.0700	0.1348	0.0594	0.1134	0.0699	0.1362	0.0616	0.1172	<i>0.0167</i>	<i>0.0624</i>
	Num.user	<b>0.0596</b>	<b>0.1664</b>	0.1452	0.2942	0.0994	0.2413	0.1403	0.2867	0.1082	0.2500	<i>0.0162</i>	<i>0.0983</i>
	Thrp.DL	0.0426	0.1553	0.0826	0.2324	0.0396	0.1616	<b>0.0377</b>	<b>0.1365</b>	0.0483	0.1745	<i>0.0315</i>	<i>0.1355</i>
	Thrp.UL	<b>0.0235</b>	0.0922	0.0252	<b>0.0879</b>	0.0247	0.0900	0.0238	0.0881	0.0320	0.1150	<i>0.0104</i>	<i>0.0735</i>
	RRC.connect	<b>0.1205</b>	<b>0.2151</b>	0.2839	0.3935	0.2503	0.3567	0.3762	0.4835	0.3245	0.4331	<i>0.0411</i>	<i>0.1242</i>
3	PRB.DL	<b>0.0123</b>	<b>0.0827</b>	0.0208	0.1070	0.0150	0.0983	0.0356	0.1542	0.0167	0.1024	<i>0.0071</i>	<i>0.0672</i>
	PRB.UL	<b>0.0318</b>	<b>0.0956</b>	0.0490	0.1414	0.0323	0.0999	0.0703	0.1727	0.0430	0.1252	<i>0.0086</i>	<i>0.0713</i>
	Traffic.DL	<b>0.0234</b>	<b>0.1100</b>	0.0328	0.1373	0.0249	0.1209	0.0566	0.1982	0.0265	0.1230	<i>0.0154</i>	<i>0.0952</i>
	Traffic.UL	0.0371	0.0993	0.0505	0.1274	<b>0.0331</b>	0.1041	0.0447	<b>0.0980</b>	0.0662	0.1319	<i>0.0092</i>	<i>0.0721</i>
	Num.user	<b>0.0209</b>	<b>0.1164</b>	0.0626	0.2047	0.0312	0.1381	0.0769	0.2276	0.0388	0.1555	<i>0.0133</i>	<i>0.0962</i>
	Thrp.DL	<b>0.0416</b>	<b>0.1242</b>	0.0484	0.1278	0.0427	0.1321	0.0720	0.1622	0.0484	0.1438	<i>0.0102</i>	<i>0.0771</i>
	Thrp.UL	0.0545	0.0994	0.0609	0.1066	0.0560	0.0916	<b>0.0542</b>	<b>0.0853</b>	0.0557	0.1046	<i>0.0074</i>	<i>0.0671</i>
	RRC.connect	<b>0.0249</b>	<b>0.1278</b>	0.1947	0.3747	0.0590	0.1967	0.3086	0.4989	0.0737	0.2310	<i>0.0145</i>	<i>0.1022</i>
Average	<b>0.0316</b>	<b>0.1111</b>	0.0653	0.1694	0.0447	0.1336	0.0752	0.1827	0.0523	0.1448	<i>0.0139</i>	<i>0.0847</i>	

MSE: mean squared error; MAE: mean absolute error. The best score of each group except fine-tuned TSNet is indicated in bold. The performance of TSNet fine-tuned with MinFT is in italics

Prediction results of TSNet and baseline methods on evaluation datasets

# Summary

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- ❑ In this paper, we propose TSNet, a novel time-series foundation model designed for network status prediction in DTs.
- ❑ TSNet demonstrates competitive zero-shot prediction capability on diverse network status measurements, achieving the best prediction results regarding MSE and MAE on average compared with fully supervised prediction models trained with historical data.
- ❑ For future endeavors, we plan to explore TSNet's capability for unified time-series representation, extending to various downstream tasks including time-series classification, anomaly detection, and pattern matching.