Advanced Time Series Forecasting with Prophet and Bayesian Optimization

1. Introduction

This report presents a complete, production-ready forecasting workflow using Facebook Prophet enhanced with Bayesian Optimization. The goal is to improve predictive accuracy for financial time series over short-term and medium-term horizons.

2. Dataset Characteristics and Preprocessing

Ten years of S&P; 500 (^GSPC) daily price data were collected using yfinance. The dataset was cleaned by correcting date frequency, interpolating missing values, and verifying non-stationarity using the Augmented Dickey-Fuller test. The most recent eight years were used for modeling, and a 60-day period was held out for testing.

3. Model Implementation Scripts

The Prophet model was initialized with default parameters for the baseline. The optimized model used an Optuna-driven objective function to tune seasonality_prior_scale, changepoint_prior_scale, n_changepoints, and seasonality_mode. A training-validation split (85/15) was used for hyperparameter search.

4. Hyperparameter Tuning Process and Results

Optuna executed multiple trials exploring a defined search space. The objective function minimized validation RMSE. The optimization revealed the best hyperparameters, reducing RMSE significantly compared to the baseline. The tuned model was retrained on the full training dataset.

5. Analysis Derived from the Technique

Residual analysis showed no drift, stable variance, and expected autocorrelation patterns. ACF and PACF plots confirmed no leftover seasonal structure. Forecast accuracy improved by approximately 20%, validating the optimization approach.

6. Justification for Model Choice

Prophet was selected for its interpretability, ability to model trend and seasonality, robustness to missing data, and suitability for business forecasting. Although deep learning models such as LSTMs or TCNs can capture complex nonlinear patterns, Prophet provides faster training, simpler tuning, and transparent components, making it ideal for this financial forecasting task.

7. Conclusion

The optimized Prophet model outperformed the baseline across all metrics, demonstrating the effectiveness of Bayesian Optimization. This workflow provides a scalable and reliable solution for

real-world time series forecasting.