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HYBRID MACHINE LEARNING MODEL IMPLEMENTATION FOR TRAFFIC PREDICTION IN SOFTWARE-DEFINED NETWORKS

ВИКОРИСТАННЯ ГІБРИДНОЇ МОДЕЛІ МАШИННОГО НАВЧАННЯ ДЛЯ ПРОГНОЗУВАННЯ ТРАФІКУ В ПРОГРАМНО-КЕРОВАНИХ МЕРЕЖАХ

Oleshchenko L. M.
Candidate of Technical Sciences,
Associate Professor,
Associate Professor at the Computer Systems Software Department
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
Kyiv, Ukraine

Олещенко Л. М.
кандидат технічних наук, доцент,
доцент кафедри програмного забезпечення комп'ютерних систем,
Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського»
м. Київ, Україна

Software-defined networking (SDN) is becoming the backbone of modern computing infrastructures due to its flexibility and centralized management of data flows. Dynamic traffic changes and high quality of service (QoS) requirements pose challenges for traditional load balancing and prediction algorithms. In this context, machine learning (ML) offers powerful tools for modeling complex patterns in network data. The study [1] evaluates a hybrid CNN-GRU model for classifying SDN traffic as normal or attack. The results show the effectiveness of combining spatial and temporal features in a deep learning model for analyzing network traffic. The paper [2] proposes an RL policy set for routing and load balancing in hybrid SDN networks. The proposed method demonstrates an improved ability to quickly adapt to dynamic traffic requirements compared to static algorithms, which highlights the promise of ML approaches in traffic engineering. In [3], multi-agent RL is used for distributed traffic engineering in hybrid SDNs. The approach allows to effectively solve scaling problems and flexibly respond to load changes in real networks, which is important for practical SDN systems. In the paper [4], a DQN-based algorithm for intelligent traffic planning in SDN is proposed, which is compared with classical methods. The results show advantages in throughput, latency, and load stability, especially under sudden traffic changes. Although the study [5] is aimed at the transport network, it demonstrates the application of hybrid models for predicting complex spatio-temporal data.

This approach is relevant for network traffic prediction, as it combines spatial and temporal dependencies into a single forecast structure. Of particular interest are hybrid models that combine classical algorithms and deep learning methods, which allow simultaneously taking into account general trends and detailed nonlinear dependencies in the prediction residuals. The works emphasize that the use of RandomForest (RF) provides stability and speed of the initial prediction, while LSTM (Long Short-Term Memory) allows to take into account sequential dependencies and complex nonlinearities in time, which is critical for the accuracy of QoS predictions in dynamic SDN environments. Recent studies confirm the effectiveness of combining traditional and deep ML methods in network prediction and management tasks.

The purpose of this research is to demonstrate the effectiveness of a hybrid ML model for predicting QoS in SDN and to justify its practical application. The proposed hybrid model combines two main components: RF and LSTM models. RF model is used for initial QoS prediction based on network characteristics. RF decision trees form an ensemble that consistently predicts general QoS trends. The advantages of this model are fast learning, interpretability, and stability of predictions in noisy data.

LSTM model is trained on the residuals of the RF, i.e. the difference between the actual and predicted QoS values. The model takes into account time dependencies and complex nonlinearities that are not taken into account by classical ML. The advantages of this model are modeling long-term temporal patterns, increasing the accuracy of the forecast. The combined approach is as follows. The basic RF forecast is corrected by the LSTM forecast, which allows obtain the final QoS value with high accuracy. Such a structure provides a balance between speed, stability and forecast accuracy.

For the SDN controller, centralized flow control was emulated (traffic generator: Poisson distribution of requests with an intensity of 200–1200 requests/s). Experiment duration was 60 min, 10 repetitions for each scenario. Metrics are average delay (ms), 95th percentile of delay (ms), load variance between servers (%), QoS prediction accuracy (MSE). Network characteristics and QoS data were collected during the first 10 min to train the model. RandomForest was trained on the baseline data.

The prediction residuals were calculated and the LSTM was trained on these residuals. Consider a fragment of the program using the hybrid model, where RF first predicts QoS based on network characteristics, and the LSTM is trained on the residuals to improve the prediction accuracy:

```
rf = RandomForestRegressor ()
rf.fit (X_rf , y_rf)
rf_pred = rf.predict (X_rf)
```

```
# LSTM on residuals to improve prediction
residuals = y_rf – rf_pred
X_lstm = np.array ([ residuals [i:i+5] for i in range (len ( residuals )-5)]). reshape (-
1,5,1)
y_lstm = residuals [5:]
model = Sequential ([
LSTM(10, activation =' relu ', input_shape =(5,1)),
 Dense (1)
])
model.compile ( optimizer =' adam ', loss =' mse ')
model.fit ( X_lstm , y_lstm , epochs =50, verbose =0)
# QoS Prediction
hybrid_pred = rf_pred [-1] + model.predict ( X_lstm [-1]. reshape (1,5,1))[0][0]
```

The code snippet presented uses a hybrid model consisting of two stages.

In the first stage, RandomForest predicts the baseline QoS based on five network metrics. In the second stage, the forecast residuals (the difference between the actual and predicted values) are fed to an LSTM, which is trained to model complex nonlinear relationships and improve the prediction accuracy. After training, the model allows combining the baseline RF prediction with the LSTM correction to obtain the final QoS value. To verify the effectiveness of the proposed approach using a hybrid model, a laboratory research was conducted in an SDN cluster environment.

The equipment included two servers with 8 vCPUs and 16 GB RAM, an SDN controller for centralized flow management, and a traffic generator with variable intensity from 100 to 1000 requests/s. The experiment lasted 60 minutes, with data for training the hybrid model collected in the first 10 minutes. The average latency, load variance, and QoS prediction accuracy were evaluated. The results showed that the hybrid approach provides an average improvement in prediction accuracy compared to using RF alone, and also reduces load variance between servers. The proposed hybrid ML model demonstrates effectiveness in predicting QoS in SDN environments through the combination of traditional machine learning and deep neural networks (Table 1).

Table 1

Average latency and load variance (60 min experiment)

Model	Medium delay (ms)	95th percentile (ms)	Dispersion load (%)
RandomForest	120	220	18
LSTM	110	210	15
Hybrid	95	180	9

RF provides fast and stable baseline prediction, while LSTM models complex temporal dependencies and adjusts the prediction residuals, which allows for more accurate results. Laboratory research has confirmed the practical value of this approach: the use of a hybrid model allows for reduced load dispersion, reduced latency, and increased QoS predictability even under variable network traffic conditions (Table 2). The load variance between servers is almost half that of the previous model, indicating a more even distribution of traffic. QoS prediction is reduced by almost half, demonstrating the high accuracy of the combined approach.

The research results can be used to build adaptive network management systems and improve the efficiency of SDN infrastructure in real conditions.

Table 2

QoS prediction accuracy

Model	**MSE of QoS prediction**
RandomForest	0.018
LSTM	0.015
Hybrid	0.009

The research confirmed that the proposed hybrid ML model can significantly improve the accuracy of QoS prediction in software-defined networks. The combination of fast basic RF prediction with LSTM residual correction allows simultaneously take into account general trends and complex temporal patterns.

Experimental results show a reduction in average latency, load variance, and QoS prediction error compared to using individual models.

The obtained data indicate the potential of integrating hybrid ML models into SDN adaptive network management systems to improve performance and stability.

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DEVELOPMENT OF A UNIVERSAL SOFTWARE TOOL FOR ASSESSING THE IMPACT OF MILITARY OPERATIONS ON LANDSCAPE AND URBAN AREAS USING CLOUD TECHNOLOGY

РОЗРОБКА УНІВЕРСАЛЬНОГО ПРОГРАМНОГО ЗАСОБУ ДЛЯ ОЦІНКИ ВПЛИВУ ВІЙСЬКОВИХ ДІЙ НА ЛАНДШАФТНІ ТА УРБАНІЗОВАНІ ТЕРИТОРІЇ З ВИКОРИСТАННЯМ ХМАРНИХ ТЕХНОЛОГІЇ

Solona I. R.
1st year Student, Group PZ-25-2,
Dnipro University of Technology
Dnipro, Ukraine

Сольона І. Р.
студентка 1 курсу групи ПЗ-25-2,
Національний технічний університет
«Дніпровська політехніка»
м. Дніпро, Україна

Актуальність теми. В умовах бойових дій в Україні дистанційне зондування Землі (ДЗЗ) є безальтернативним методом безпечного моніторингу інфраструктурних та екологічних збитків на недоступних територіях. Широке використання комерційних супутникових платформ обмежується високою вартістю та закритою архітектурою, а десктопних геоінформаційних систем (наприклад, QGIS) – надмірними вимогами до локальних обчислювальних потужностей. З огляду на це, розробка автоматизованих хмарних алгоритмів є критично актуальним завданням, виконання якого дозволить оперативно документувати руйнування, оптимізувати ресурси та мінімізувати суб'єктивний людський фактор.