Digital Twin-Enhanced Framework for TCP Throughput Map Construction in Dynamic IoV

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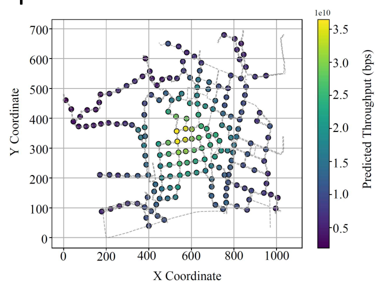
Background

- **Intelligent Transportation** relies on efficient data collection to support real-time decision-making and traffic optimization.
- **Transmission Control Protocol** (**TCP**) **Throughput Value** is a key metric that directly reflects network transmission performance in road transportation.

Building real-time **TCP Throughput Maps**, which aims to identify network bottlenecks, is becoming more and more important



The TCP Throughput Heatmap

Challenge

- **Limited Communication Resources of the Base Station**– Bandwidth and spectrum constraints in vehicular networks.
- **High Data Collection Costs of the Sensor**– Real-time network performance data acquisition requires huge sensing cost.
- **Dynamic IoV Conditions**– High-speed vehicle movement and dynamic channel conditions make accurate TCP throughput map construction more challenging.

These factors hinder effectively **TCP Throughput data collection** and **TCP throughput maps construction**

Related Works

- Integration of Digital Twin (DT) Technology in Sensing and Communication

  DT has been applied to sensing and communication for channel estimation [1], data processing optimization [2], and vehicular tracking & beamforming [3].
  In vehicle edge computing, DT enhances communication resource allocation [4].

Existing studies focus on traditional sensing and communication for **physical objects** and **do not integrate TCP throughput as a sensing target**

[1] J. Zhang and et,al.,"Digital-twin-enabled sensing channel estimation for 6g cell-free isacmimo system," in 2024 IEEE WCNC, 2024, pp. 1–6.

[2] S. Hu and et,al., "Digital twin-based user-centric edge continual learning in integrated sensingand communication," ICC 2024, pp. 5646–5651.

[3] W. Ding and et,al., "Jointvehicle connection and beamforming optimiziation in digital-twin assistedintegrated sensing and communication vehicular networks," IEEE IoTJ, vol. 11, no. 20, pp. 32 923–32 938, 2024.

[4] Y. Gong and et,al., "Resource allocationfor integrated sensing and communication in digital twin enabled internetof vehicles," IEEE TVT, vol. 72, no. 4,pp. 4510–4524, 2023.

Introduction

Related Works

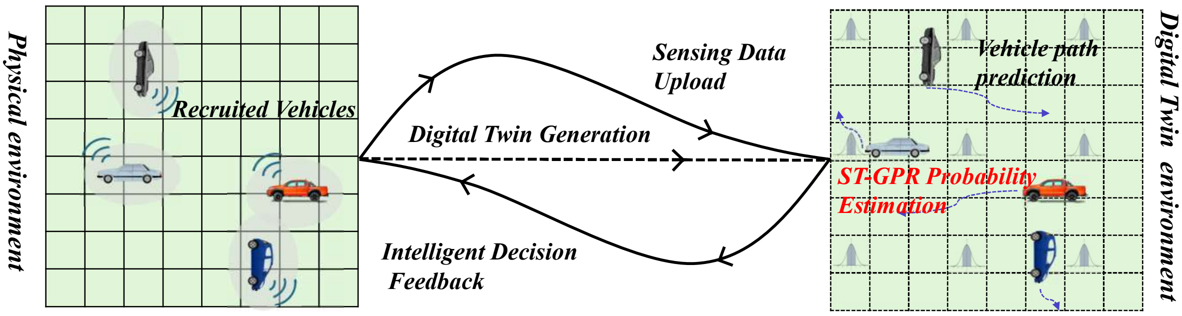
➢ Spatio & Temporal TCP Throughput Map Modeling

Spatial correlation: Studies focus on TCP throughput analyze transmission errors and congestion losses in heterogeneous environments [5].
Temporal correlation: Studies focus on Round-Trip Time (RTT), buffer size, and queueing effects, revealing the dependency of throughput stability on network fluctuations [6].

Existing studies analyzed spatial and temporal dependencies separately, **failing to capture their joint spatio-temporal interactions**

[5] H. D. Le and et al., "Throughput analysis for tcp over the fso-based satellite-assisted internet of vehicles," IEEE TVT, pp. 1875–1890, 2022.
[6] L. Bommisetty, "Performance analysis of tcp queues: Effect of buffer size and round trip time," in 2021 6th ISPCC, pp. 631–635.

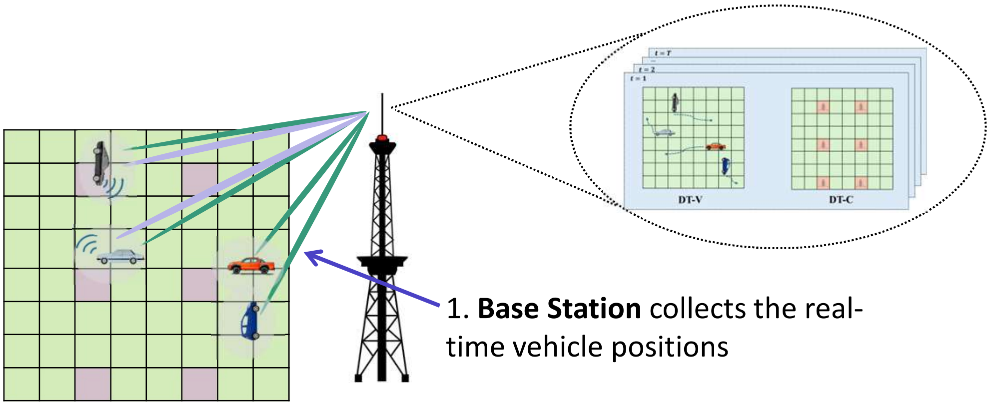
Our Goals



The Overview of Our System

We construct a **Spatio-Temporal Gaussian Process Regression (ST-GPR)** – based **TCP Throughput Maps** by **recruiting a limited number of vehicles.**

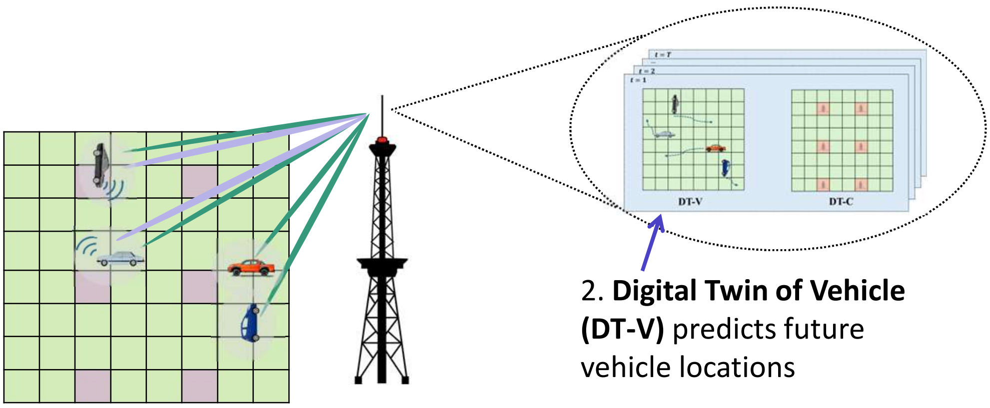
System Overview



1. **Base Station** collects the real-time vehicle positions

The Workflow of Our System

System Overview

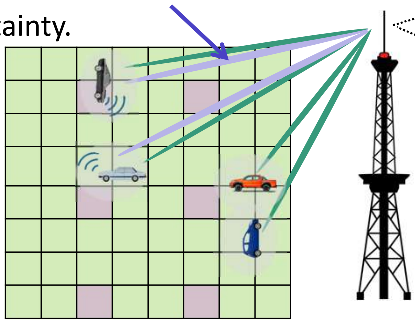


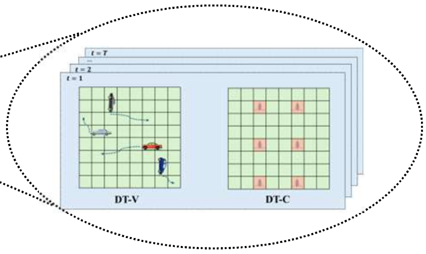
2. **Digital Twin of Vehicle (DT-V)** predicts future vehicle locations

The Workflow of Our System

System Overview

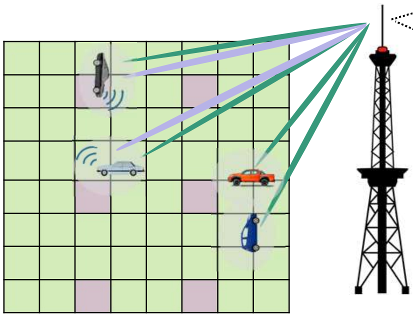
3. **Base Station** selects vehicles to monitor TCP throughput by analyzing the predicted vehicle locations from DT-V and the TCP throughput uncertainty.

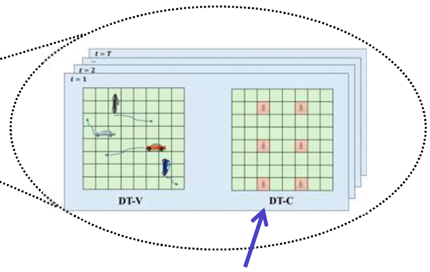




The Workflow of Our System

System Overview





4. **Digital Twin of Certainty (DT-C)** Update the TCP throughput map based on the Uncertainty Value of the map and TCP throughput prediction value

The Workflow of Our System

Our Model

Spatio-Temporal GPR Model for TCP Throughput Map

- Spatio-Temporal Kernel Function [7]:

$$k_{ST}(v_m, g_n) = \beta^2 \cdot \boxed{\exp(-\frac{\|z_m - z_n\|^2}{2l_s^2})} \cdot \boxed{\exp(-\frac{|t_m - t_n|}{2l_t})}$$

Space decay rate Time decay rate

- Mean Value (Predict the **TCP throughput value** of each observation point):

$$\mu(g_n^t) = \sum_{v_m \in S^t} \omega(v_m, g_n) \cdot T(v_m) = \sum_{v_m \in S^t} \frac{k_{ST}(v_m, g_n)}{\sum_{v'_m \in S^t} k_{ST}(v'_m, g_n)} \cdot T(v_m)$$

- Variance Value (Calculate the **uncertainty** of each observation point) :

$$\sigma(g_n^t) = max(0, \sigma(g_n^{t-1}) - k_{ST}(g_n^t, S^t))$$

[7] T. Gao, T. Nattaon, Y. Ohsit, and H. Shimonishi, “Robot path planning for monitoring dynamic environment by predictive uncertainty minimization using gaussian process regression,” IEEE 43rd ICCE, 2025.

Proposed Model

TCP Throughput Map Uncertainty Minimization

- TCP throughput map uncertainty at time slot t: $U(t) = \boxed{\sum_{g_n \in G} \sigma(g_n^t)}$
- TCP throughput map uncertainty over time interval: $\mathcal{U} = \int_t^{t'} U(t)\, d(t) = \int_t^{t'} \boxed{\sum_{g_n \in G} \sigma(g_n^t)} d(t)$
- TCP throughput map uncertainty minimization:

$$min_{S^t} \int_t^{t'} \boxed{\sum_{g_n \in \mathcal{G}} \sigma(g_n^t)} dt \quad s.t. \sum_{v_m \in S^t} \mathbf{1}(v_m^t) \leq K^t, \forall t, S^t \subseteq \mathcal{V}^t, g_n \in \mathcal{G}$$

We propose a **Fixed-Observation Rolling Optimization Algorithm (FOROA)**

Proposed Algorithm

FOROA

- **Objective**: Select limited vehicles to reduce the uncertainty of TCP throughput maps.
- **A Three-Stage Process**:

Window Size

① **Observation s^t**: Observes vehicle movements over a fixed window size c

$$s^t = (\{z_m^{t+1,\dots,t+c}\}, z_n^t, \{\sigma(g_i^{t-1}) \mid i = 1, \dots, N\}, V^t)$$

② **Evaluation r^t**: Evaluates vehicles' contribution for the uncertainty reduction

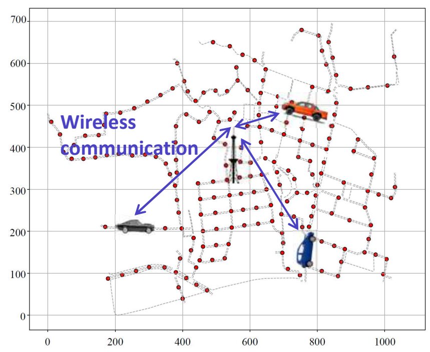
$$r^t = \sum_{g_n \in G}(\sigma(g_n^{t-1}) - \sigma(g_n^t))$$

No. of Vehicles Selected in One Subset

③ **Selection a^t**: Selects an optimal subset of vehicles $S^t \subseteq V^t$

$$a^t = S^t, \; S^t \subseteq V^t$$

Simulation- Wireless Communication Modeling



Communication Diagram Between Base Station and Vehicles

1 Base Station, 304 observation points, 60 vehicles

Channel Parameters:
- Path Loss Exponent: 4.0
- Absorption Loss: 15 dB
- Scattering Loss: 5 dB

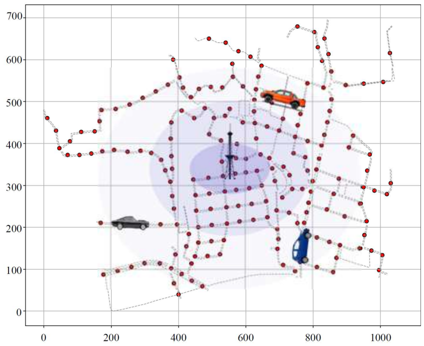
Beyond 5G Parameters:
- Bandwidth: 10 GHz
- Transmission Power: 30 dBm
- Noise Power: -100 dBm

Signal-to-Noise Ratio (SNR) :

$$SNR_{linear} = 10^{\frac{P_{Received} - P_{noise}}{10}}$$

We consider wireless communication based on **beyond 5G**

Simulation – TCP Throughput Modeling



TCP throughput distribution Diagram

Key Factors:

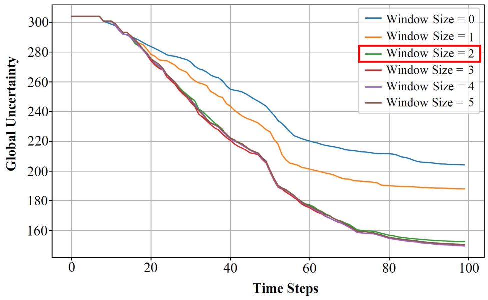
Channel state (SNR - Signal-to-Noise Ratio)
Path loss (Distance & Absorption Loss)
Local vehicle density (neighboring vehicles count)
Congestion control (TCP window size)
Round-Trip Time (RTT)

Throughput Value:

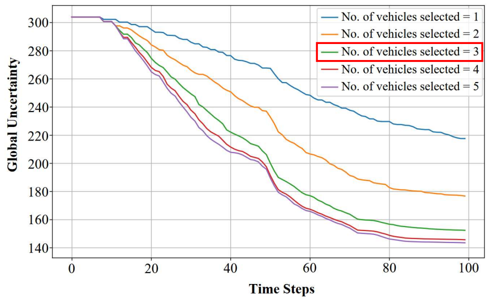
$$Throughput = Blog_2(1 + SNR_{linear})$$

We considered a TCP throughput distribution model influenced by **multiple parameters**

Our Results - Convergence Analysis of FOROA



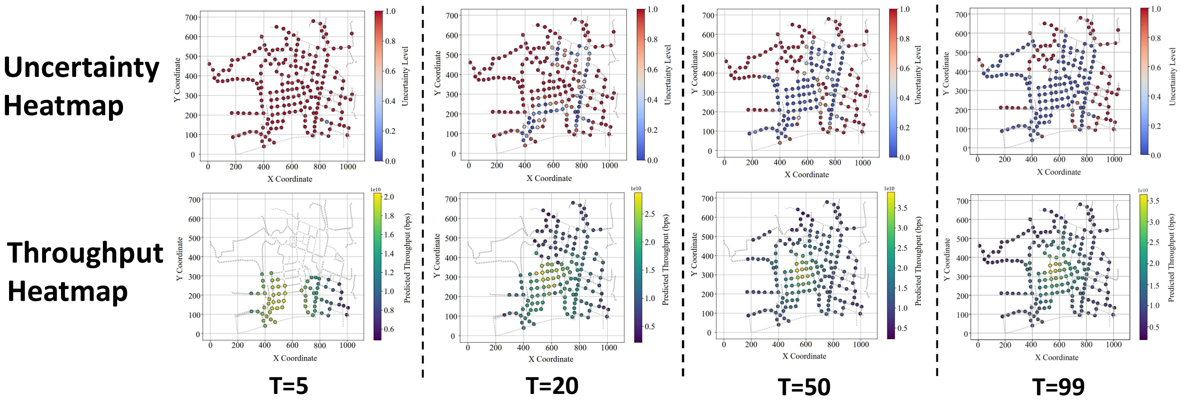
Window Size Impact on the Uncertainty



Number of Vehicle Selected Impact on the Uncertainty

We fix the **window size at 2** and **the number of vehicles at 3** per time step to balance uncertainty reduction, computational efficiency, and data collection cost

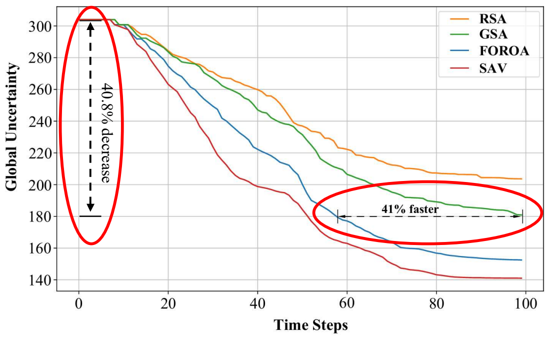
Results - Uncertainty & TCP Throughput Heatmap



Our algorithm efficiently updates the **uncertainty heatmap** and the **TCP throughput distribution heatmap**

Results -

- **Select All Vehicles (<u>SAV</u>):** Select all available vehicles at each time step.
- **Greedy Selection Algorithm (<u>GSA</u>):** Sequentially select three vehicles by prioritizing the immediate reduction of TCP throughput uncertainty at each time step.
- **Random Selection Algorithm (<u>RSA</u>):** Randomly selects up to three vehicles per time step



Comparison of FOROA with Other Algorithms

Our algorithm achieves **41.0% faster than GSA** when reducing map uncertainty by 40.8%

Conclusion & Future Plan

Conclusion

- **Spatio-Temporal GPR for TCP throughput modeling**: Integrated within a Spatio-Temporal GRR function, enables TCP throughput map construction and uncertainty quantification.
- **Innovative vehicle selection**: Introduced FOROA, ensuring accurate map construction despite resource constraints in high dynamic IoV.

Future Plan

- Develop a digital twin-based vehicle trajectory prediction system (DT-V).
- Implement our model in real-world applications.

THANK YOU

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