January 17, 2025

Advanced Frameworks for Communication, Learning, and Decision-Making in Digital Twin-Based Vehicular Networks

Ph.D. Proposal
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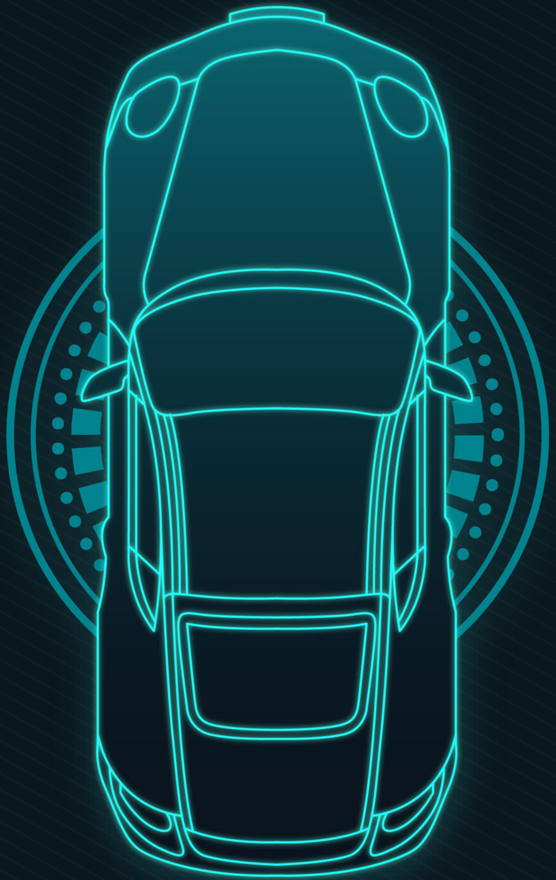

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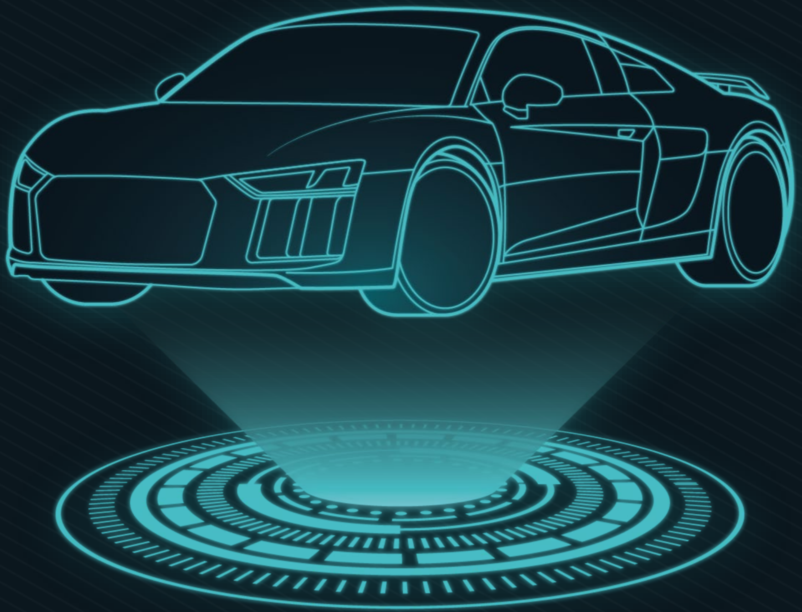
Introduction



What is IOT

- Internet of Things (IoT) is a system of devices connected to the Internet with the ability to collect and exchange data from users or the environment with no human intervention

- The devices or things in IoT could be any device embedded with electronics, software, and sensors like a smart refrigerator, a smart air conditioner, lights in the household, connected security systems, or even a person with a heart monitor or an automobile.

Consider the SITUATIONS

- Traffic Management and Congestion Scenarios
  - Traffic Conditions, Accidents, and Road Closures
- Emergency Scenarios
  - Natural Disaster
- Collision Avoidance Scenarios
  - Speed Warnings to Drivers
- Parking Issues
  - Exact Location
- Public Transportation
  - Delays, Alternative Routes

Google MAPS

- Source of Information
  - Historic Traffic Patterns, Road Sensors, and data from smartphones
- Google Maps may have latency and might not capture rapidly changing situations
  - Emergency Response
- Google Maps is good for Highways but might not for smaller roads
- User-Generated Data

Fake Traffic Jam on Google Maps

- In the Year 2020, Man Used 99 Phones in a Wagon to Create a Fake Traffic Jam on Google Maps
- With his "Google Maps Hack," artist **Simon Weckert** draws attention to the systems we take for granted

Vehicular Ad hoc Network (VANET)

- Bunch of vehicles connected through a network

- VANET connects two or more vehicles wirelessly to enable data exchange in an Internet of Things(IoT) environment

- Unlike Google Maps, relies on direct communication V2V and V2I

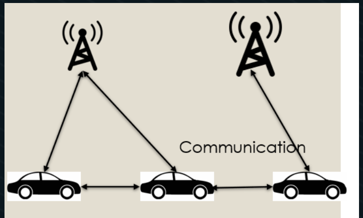
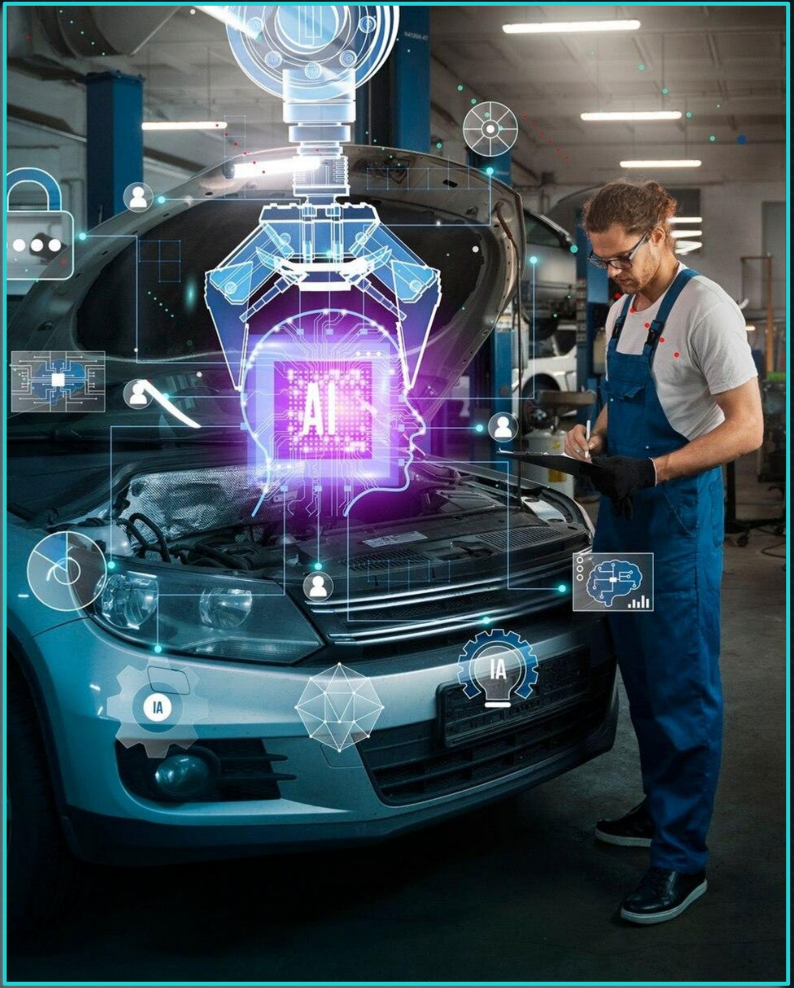


Fig: Vehicular Ad Hoc Networks

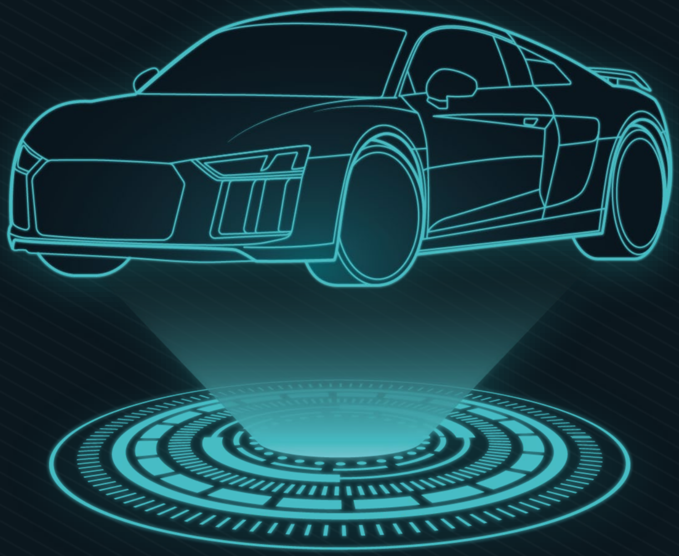


Consider The ISSUES

- Limited Storage
- Limited Geographic Coverage
- Limited Analysis
- Limited Decision Making
- Limited Resources

Digital Twins

- Based on a virtual representation of the physical environment
- Digital Twins can address the issues of VANET by utilizing cloud storage
- Scalable Computational Resources, Enhancing Security & Privacy and Optimize Resources Utilization.



Still Something Lacking

- Exchange of Raw, sensitive, and Private information to the central Server/Cloud
- Communication Overhead
- Struggle to adopt dynamic scenarios
- Scalability to process large volumes of data centrally
- Emergency Vehicle less response time
- Customized prediction
- Data heterogeneity
- Real time decision making

Proposed Aims

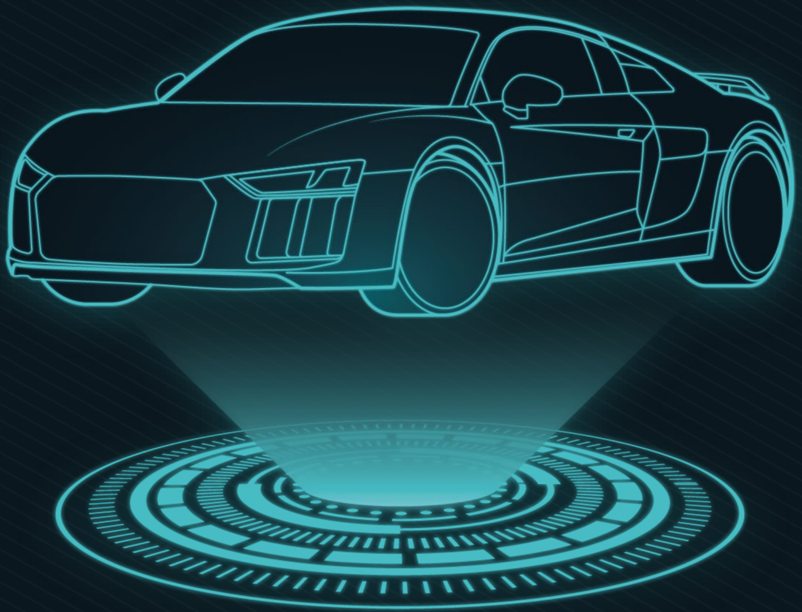
Aim 1: Minimize Emergency Vehicles Response Time

Aim 2: Minimize Convergence Time and Customize prediction for each vehicle category

Aim 3: Real-Time Decision Making

02

Priority Based Inter-twin Communication in Vehicular Digital Twin Networks



Overview

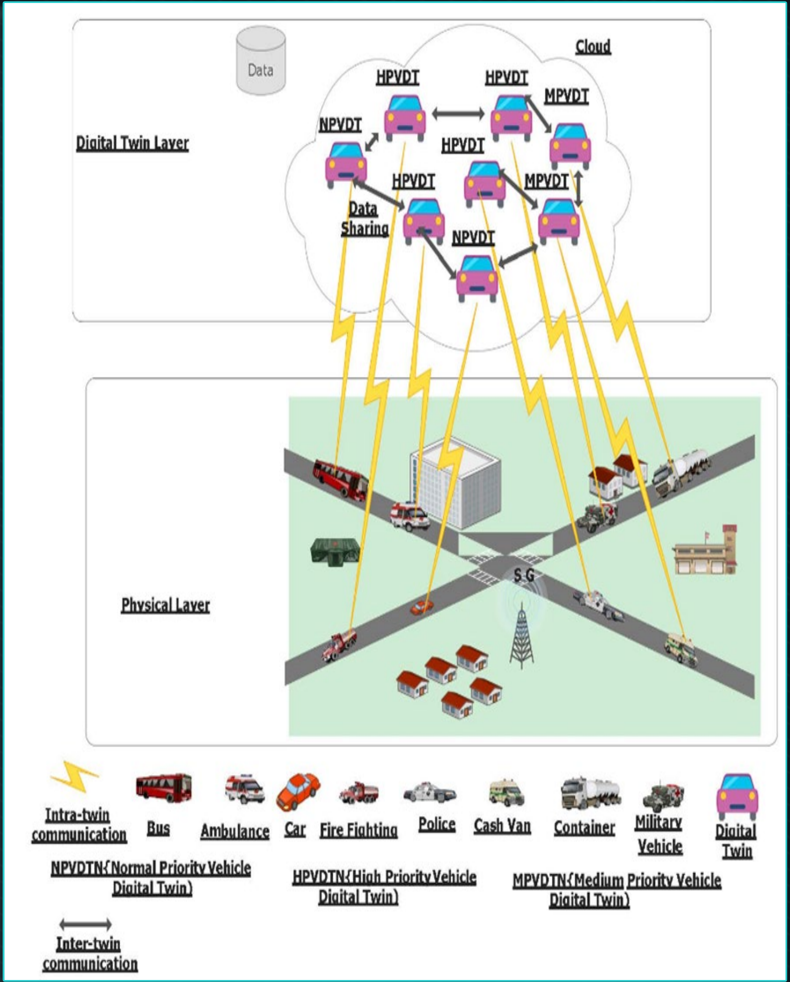
Introduction

- Same processing preference
- Same sharing preference
- Substantial Communication Overhead

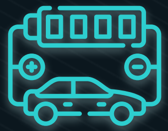
Priority based Inter Twin DTVN

Motivation

- Ideal and rapid emergency services and mobility infrastructure in vehicular networks
    - Priority of different DT while allocating resources
    - The communication between DT have been challenging at the Physical Layer
    - High Priority Vehicle require response as soon as possible



Problem Statement



“How can we reduce the Response Time of Emergency Vehicles in DT-VANET?”

Vehicles and Application Categories

Table 2. Brief description of categories related to vehicles.

Vehicle Priority	Categories of Vehicles
High Priority Vehicles	Police, Army, Customs, Ambulances, Law Enforcement Agencies, Fire Departments, Mobile Medical Units, and Detainees Vehicles.
Medium Priority Vehicles	Medical Association, Cash transportation, Blood Products contain vehicles, Human organs vehicles, and sanitary transport vehicles.
Normal Priority Vehicles	Private Vehicles, Vans, Goods Transport, Passenger Carrying vehicle.

Table 3. Brief description of categories related to vehicles applications.

Application Priority	Categories of Applications
First Priority Applications	Safety Applications
Second Priority Applications	Traffic Management Applications
Third Priority Applications	Efficiency Applications
Fourth Priority Applications	Information and Entertainment Applications
Fifth Priority Applications	Social Applications

Algorithm 1

Algorithm 1 Intra-Twin Communication Update

1. Initialize Data Upload:

(a) Each vehicle m carries certain independent private data, *PD*, related to the vehicle;

(b) It uses existing networks, base stations, and wireless communications (5G, WiFi), in this regard, which resides at the physical layer.

2. Data Processing at Digital Twin Layer

for each update $k = 0, 1, 2, \ldots, k - 1$ **do**

INTER-TWIN(PD);

3. Obtain the final updated private information, *PI*, from the digital twin layer to the base station, and transmit it back to the corresponding vehicle.

Algorithm 2

Algorithm 2 Inter-Twin Communication Priority Update

Input: The data that needs to be processed from the base station **B** to the respective digital twin (**DT**);
Output: The processed information from the respective digital twin (**DT**) to the base station **B**;

INTER-TWIN(*PD*) :
(I). For high-priority vehicle DT:
Receive *PD* from the base station;
Record the resources it requires into collection $Resource_{high}$;
for all resources $r \in Resource_{high}$ **do**
    if $r \notin DT_{high}$ then
      Send *PD* to *r*;
      Receive *PD* from *r*;
      Update *PD*;
    else if
      AppPriority();
    else
      FCFS();
    end if
end for
Send PD to the base station;

(II). **For medium-priority vehicle DT:**
Receive *PD* from the base station;
Record the resources it requires into collection $Resource_{medium}$;
for all resources $r \in Resource_{medium}$ **do**
    if $r \notin DT_{medium}$ and $r \notin DT_{high}$ then
      Send *PD* to *r*;
      Receive *PD* from *r*;
      Update *PD*;
    else if $r \in DT_{medium}$
      AppPriority();
    else
      FCFS();
    end if
end for
Send *PD* to the base station;

(III). **For normal-priority vehicle DT:**
Receive *PD* from the base station;
Record the resources it requires into collection $Resource_{normal}$;
for all resources $r \in Resource_{normal}$ **do**
    if $r \notin DT_{normal}$, $r \notin DT_{medium}$ and $r \notin DT_{high}$ then
      Send *PD* to *r*;
      Receive *PD* from *r*;
      Update *PD*;
    else if $r \in DT_{normal}$
      AppPriority();
    else
      FCFS();
    end if
end for
Send *PD* to the base station;

BEHIND THE SCENES

Dataset

(https://vehicular-mobility-trace.github.io/index.html#dataset).

Data Cleaning

Data Cleaning, Pre-Processing and Normalization

Comparison Algorithms

-Throttled Load Balancing
-Round Robin Algorithm
-Priority Algorithm

Performance Metrics

Message Delivery Rate

Latency

Bandwidth Utilization

Response Time

Throughput

Resource Utilization

Communication Overhead

Experimental Results

Table 5. Experimental results regarding the average performance metrics across a couple of algorithms with Priority Algorithm.

Algorithm	MDR	LAT	BU	TP	RT	RU	FAIR	CO	ADC	FT	AC
Round Robin	6.6881	9.8850	6.6882	6.6884	9.8852	0.0667	1.227	33.2	0.546	0.00	14.0
Throttled Load balancing algorithm	6.6770	9.8849	6.6771	6.6773	9.8851	0.0666	1.232	33.3	0.547	0.00	11.0
Priority Based VDTN algorithm	6.6883	9.8830	6.6884	6.6886	9.8832	0.0668	1.233	33.0	0.549	0.00	8.0

Note: MDR = Message Delivery Rate (messages), LAT = Latency(ms), BU = Bandwidth Utilization(%), TP = Throughput(messages/s), RT = Response Time(ms), RU = Resource Utilization(%), FAIR = Fairness, CO = Communication Overhead (messages/s), ADC = Adaptability to Dynamic Changes, FT = Fault Tolerance, AC = Algorithm Complexity

The proposed Algorithm produces better values for Message Delivery Rate (MDR), Bandwidth Utilization(BU), Throughput(TP), Resource Utilization(RU), Fairness and Adaptability to Dynamic Changes(ADC), and low values for Latency, Response Time(RT), Communication Overhead(CO) and Algorithm Complexity (AC) which confirm our algorithm efficiency over them

*100 Simulations

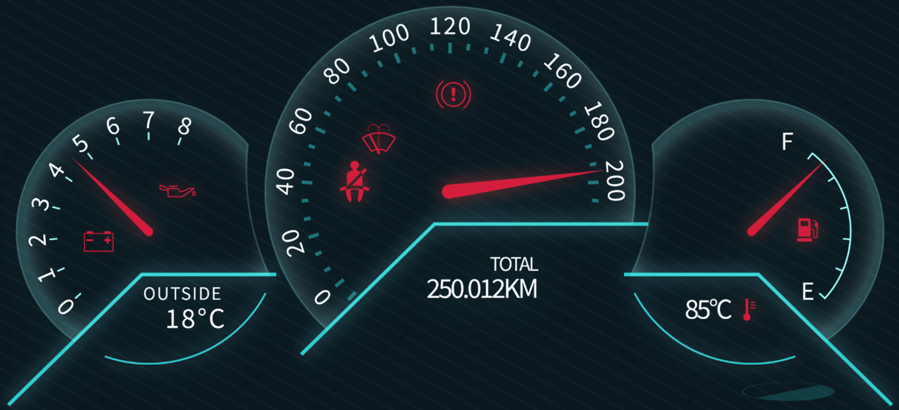
Experimental Results

Table 6. Experimental results regarding the average scalability metrics across a couple of algorithms with Priority Algorithm.

Algorithm	SV	MDR	LAT	BU	TP	RT	RU	FAIR	CO	ADC	FT	AC
Round Robin	10	0.665	9.9	0.666	0.668	9.7	0.069	1.130	3.4	0.72	0.00	11.0
	20	1.338	9.85	1.339	1.340	9.88	0.069	1.16	7.3	0.64	0.00	11.0
	30	1.998	9.90	1.94	1.96	9.87	0.066	1.17	10.2	0.651	0.00	11.0
Throttled Load balancing algo	10	0.651	9.8	0.670	0.672	9.6	0.073	1.139	3.2	0.71	0.00	14.0
	20	1.346	9.86	1.347	1.350	9.80	0.073	1.18	7.0	0.65	0.00	14.0
	30	1.990	9.98	1.93	1.94	9.88	0.063	1.18	9.8	0.619	0.00	14.0
Priority Based VDTN algo	10	0.672	9.7	0.673	0.675	9.5	0.076	1.151	3.1	0.74	0.00	10.0
	20	1.349	9.76	1.350	1.352	9.64	0.074	1.19	6.6	0.66	0.00	10.0
	30	2.005	9.86	2.00	1.99	9.84	0.068	1.19	9.4	0.656	0.00	10.0

Note: SV = No of Vehicles Scale, MDR = Message Delivery Rate (messages), LAT = Latency(ms), BU = Bandwidth Utilization(%), TP = Throughput(messages/s), RT = Response Time(ms), RU = Resource Utilization(%), FAIR = Fairness, CO = Communication Overhead (messages/s), ADC = Adaptability to Dynamic Changes, FT = Fault Tolerance, AC = Algorithm Complexity

Proposed Algorithm produces better values for Message Delivery Rate(MDR), Bandwidth Utilization(BU), Throughput(TP), Resource Utilization(RU), Fairness and Adaptability to Dynamic Changes(ADC) and low values for Latency, Response Time(RT), Communication Overhead(CO) and Algorithm Complexity(AC) which confirm our algorithm efficiency over them

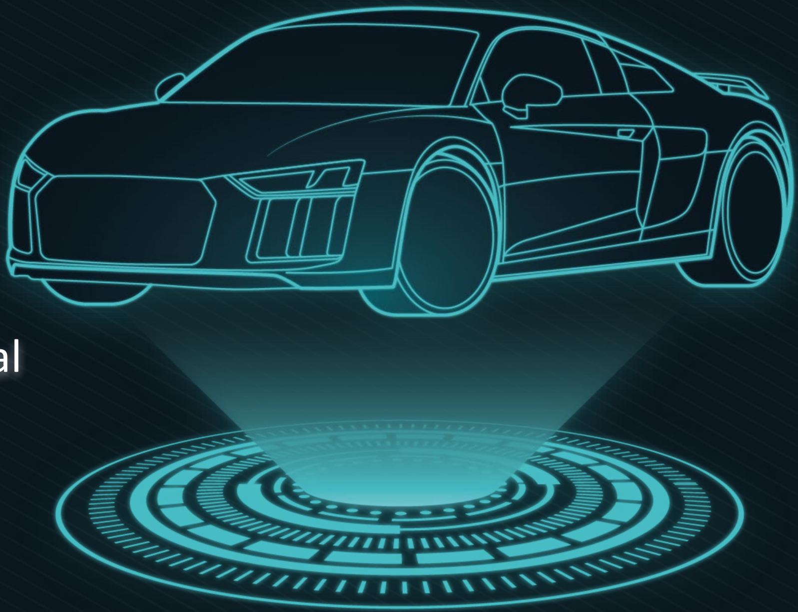


- Efficient Priority-Based Model
- Intra and inter-twin communication algorithms to minimize communication overhead
- Demonstrated effectiveness through experiments with real datasets and scalability tests

—Conclusion

03

Hierarchical Federated Transfer Learning in Digital Twin-Based Vehicular Networks



Overview

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Introduction

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HFTL in VDTN

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Problem Statement

Federated Learning

- Enables central model training on decentralized data
- The training process involves sending model updates from local devices to a central server
- Solution to user privacy, communication overhead, struggle to scalability and dynamic scenarios
- Applications Traffic Flow Prediction, Collision Risk Prediction, Route Planning and Optimization, Vehicular Communication Reliability Prediction, Energy Consumption Prediction, Smart Parking Prediction, Environmental Impact Prediction

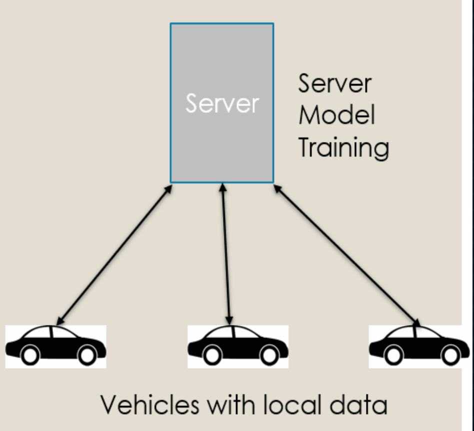


Fig: Federated Learning

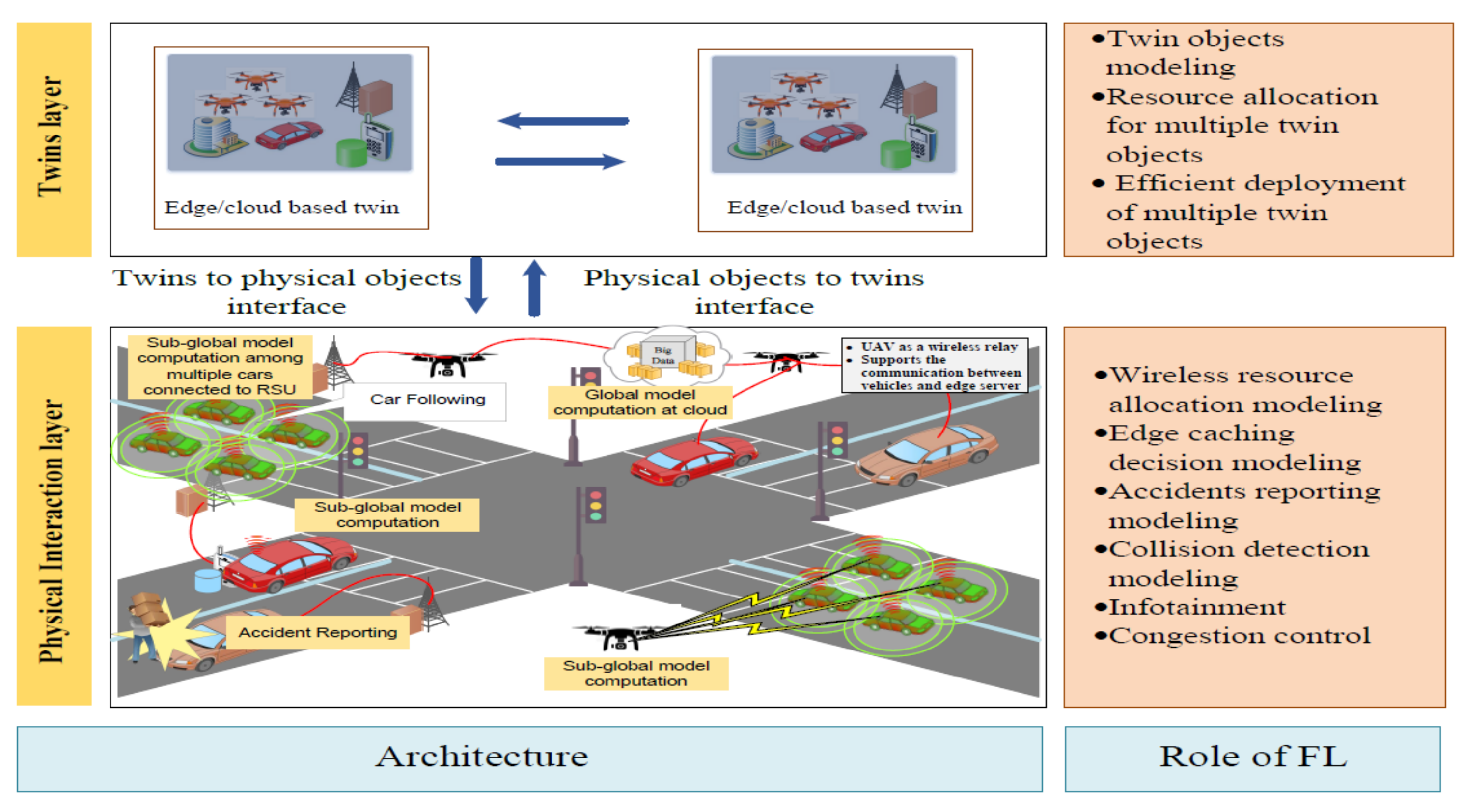
Most Recent Architecture

"Federated Learning for Digital Twin-Based
Vehicular Networks: Architecture and Challenges"

- There is one most Architecture published in March 2023, in IEEE Wireless Communication

- It utilizes all the basic three concepts that we have discussed before in an Architecture

Proposed Architecture of Federated Learning for DT-VANET



Sequence Diagram

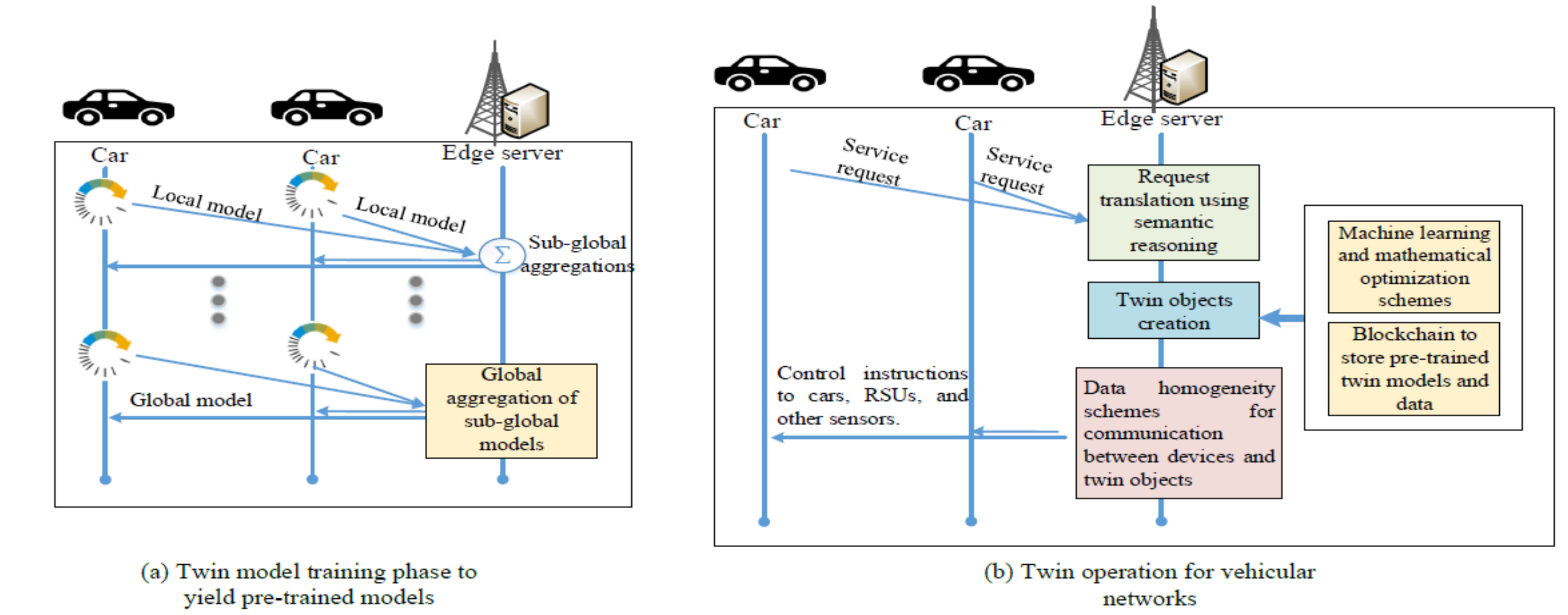
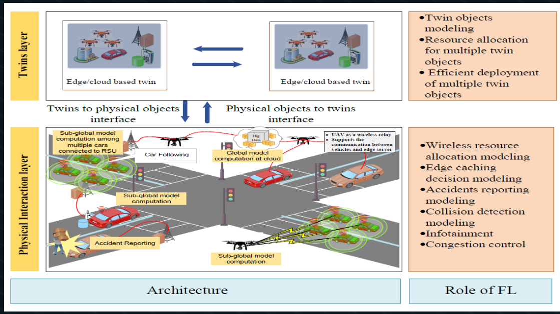


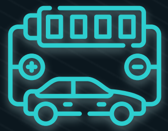
Fig. 2: Sequence diagram of (a) offline twins training using DFL, and (b) online twin-based vehicular network operation

IN-DEPTH ANALYSIS

- Communication Overhead
- Heterogeneity
- Vehicles with a limited amount of data may result in overfitting(New or Classic Vehicles)
- Trustworthiness Metrices (Incentivization)
- Data Reduction
- Communication Secure
- Fault Tolerance



Problem Statement

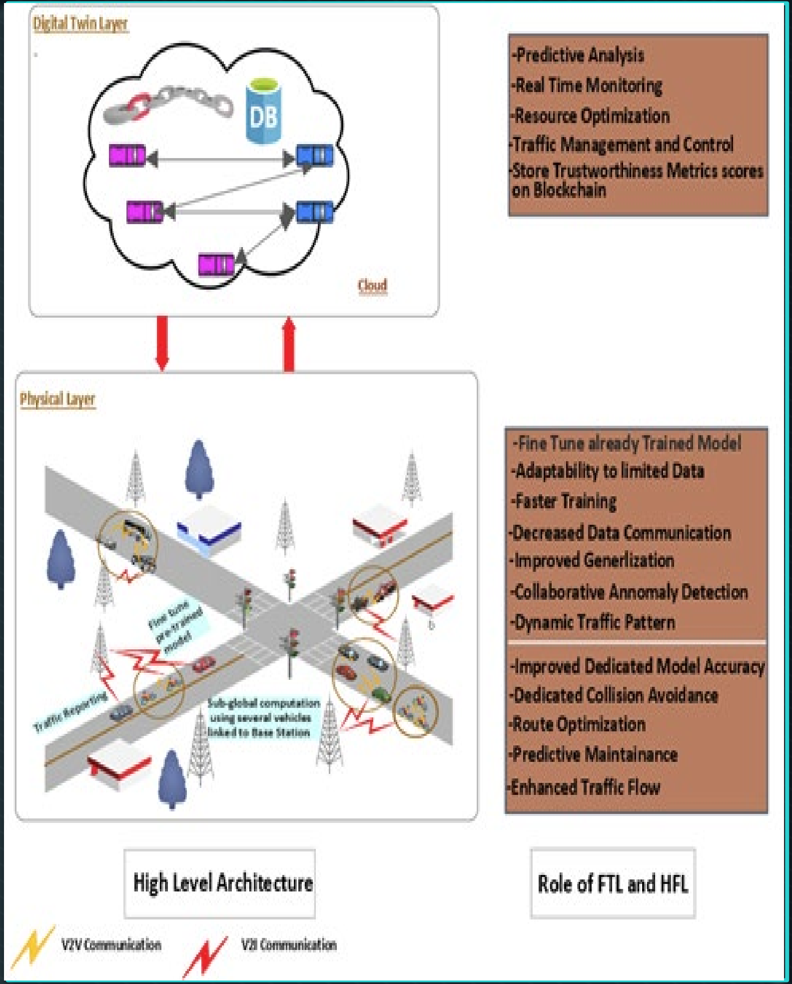


“How can we achieve faster convergence and customized prediction in DT-VANET?”

Hierarchical FTL in VDTN

Motivation

- Federated Learning struggles with data heterogeneity and data sparsity
- To address these challenges, Federated Transfer Learning is used
  - Clustering based on Vehicle Types
  - Personalized Fine- Tuning Models
  - Use blockchain and Data Quality Score to prevent malicious vehicle



TIPS & TRICKS (Solutions)

Hierarchical Federated Learning

“Cluster Vehicles basis on Vehicle Size, Purpose, Patterns and Resources”
From Clustering we can reduce communication overhead

Federated Transfer Learning

“To improve convergence and heterogeneity. Fine-tune a pre-trained model for task and vehicle type. Now we can train on vehicles with less data ”

Trustworthiness Metrices

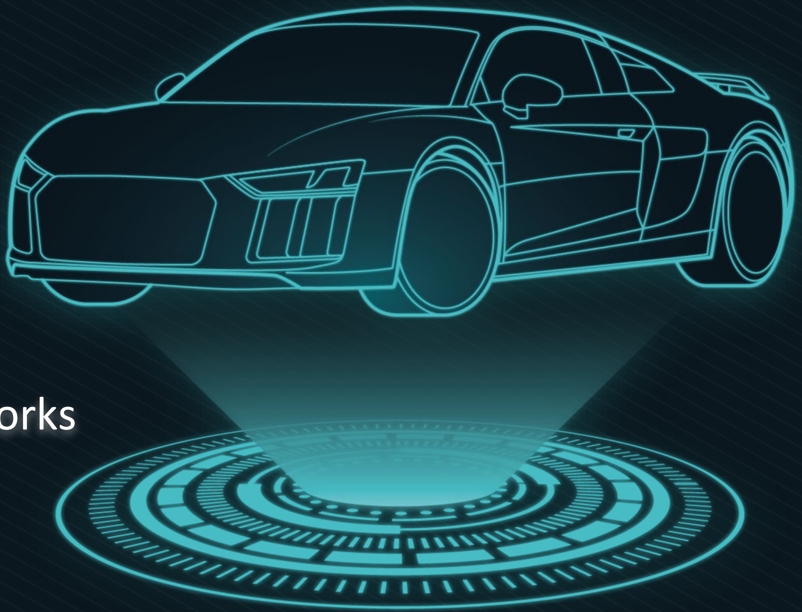
“Determine the score based on data completeness, sensor collaboration, safe and reliable driving, and challans. Store it on the cloud blockchain for detecting future anomalies ”

Fault Tolerance

“In this case, Cluster Head will be replaced with the vehicle with the most advanced features, and vulnerable vehicles backed up on clouds after rush hours usually at night e.g. old, heavy, high mobile and poorly maintained vehicle ”

04

Optimized Real-Time Decision Making with EfficientNet in Digital Twin-Based Vehicular Networks



Overview

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Optimized Decision Making in VDTN

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Problem Statement

Introduction

- Real Time decision making
- Traffic Efficiency and Flow
- Road Safety

Data Latency and Volume

The Rapid Generation of Data from different sources.

Computational Complexity

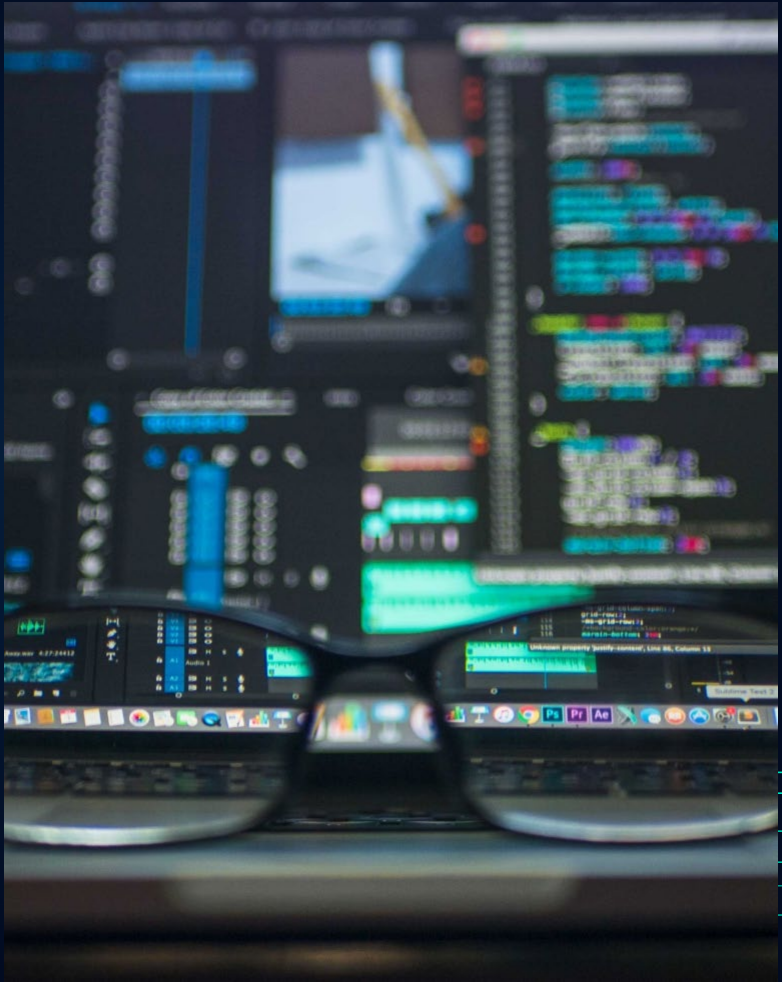
Complex Models and Computations

Model Efficiency

Traditional deep-learning models are powerful but not good real-time applications

Decision Quality

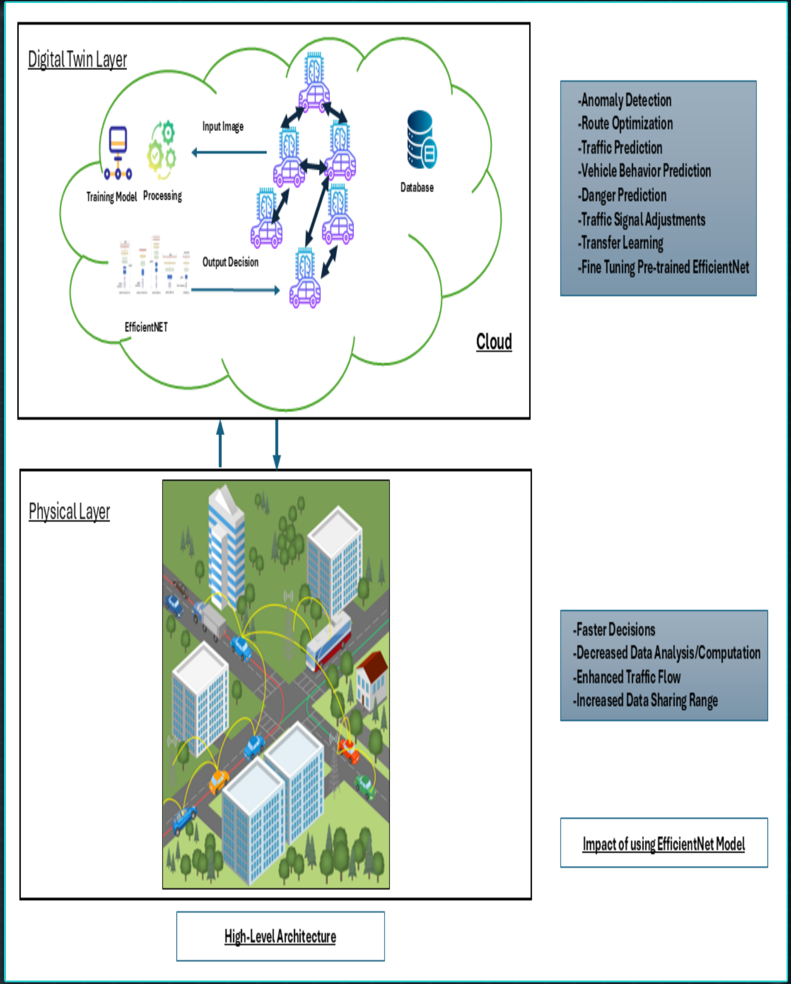
Decisions are optimized for minimizing accidents



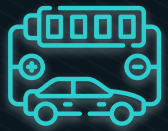
Optimized Real Time DM in DTVN

Motivation

- Real-Time Decision Making is vital in DTVN
- Challenges:
    - Latency
    - Computational Resources

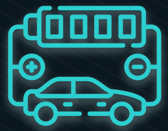


Problem Statement



"How can we make faster and optimized decision-making in DT-VANET?"

EFFICIENTNET



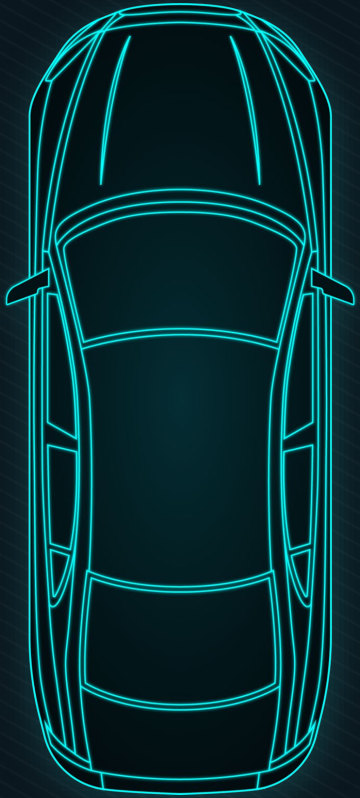
EfficientNET is a lightweight CNN model that is known for

- Fast and Accurate Decision Making
- Less Computational Cost
- Convenient for evaluating and forecasting data real-time

List of Publications

Here's a list of publications until now.

- A Local Differential Privacy Trajectory Protection Method Based on Temporal and Spatial Restrictions for Staying Detection
- DPTP-LICD: A differential privacy trajectory protection method based on latent interest community detection
- Bilateral Privacy Protection Scheme Based on Adaptive Location Generalization and Grouping Aggregation in Mobile Crowdsourcing
- Priority-based inter-twin communication in vehicular digital twin networks



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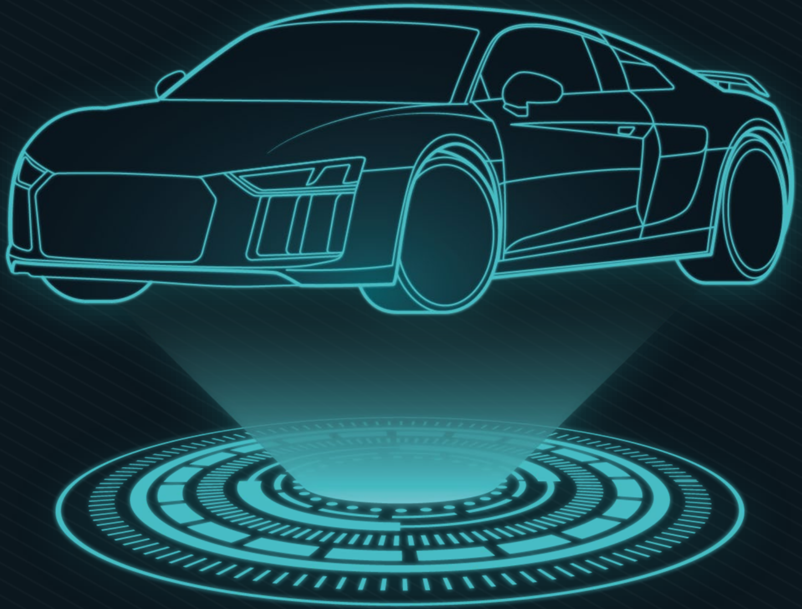
Future Work



Completion Status

Aim 1: Completed

- Proposed a priority algorithm for DT-VANET
- Published a paper in the Taylor and Francis Journal

Aim 2: In Progress

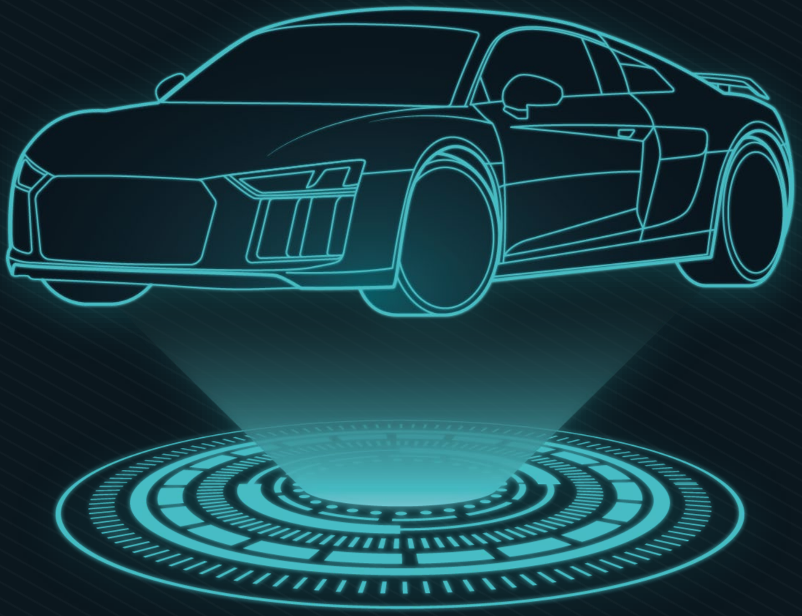
- Hierarchical Federated Transfer Learning for DT-VANET
- Make clusters on vehicle type and use Federated Transfer Learning

Aim 3: In Progress

- Real Time Decision Making for DT-VANET
- EfficientNET is a lightweight CNN model convenient for real-time decision making

06

Tentative Timeline



January 17

Research on vehicular networks issues, and their mitigation in DTN

March 1

Manuscript Writing for FL issues in VDTN

APRIL 15

Background Research and Data Collection

May 20

Research on real time decision making issues, and their mitigation in DTN

June 15

Manuscript Writing for Real-time decision-making issues in VDTN

June 30

Background Research and Data Collection

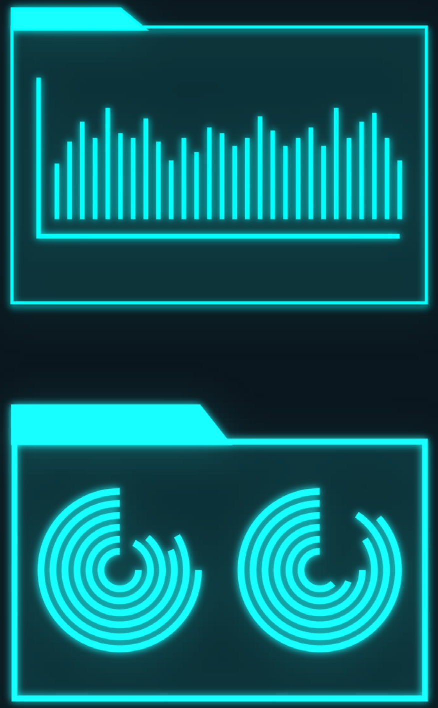
July 15

Tentative Dissertation Writing

July 30

Tentative Dissertation Defense

THANKS
Any Questions?



References

- Slides Template by Slidesgo, Flaticon and Freepik