A Mobile Edge Computing Framework for Traffic Optimization at Urban Intersections through Cyber-Physical Integration

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***Abstract*—The stop-and-go traffic pattern on urban roads often results in excessive energy consumption due to unnecessary vehicle braking, idling, and accelerations back to free flow speed. With the widespread and increased use of automobiles, this traffic pattern creates many negative impacts (e.g., delayed travel time, air pollution, and additional carbon emission) on the urban livability and environments in cities worldwide. Taking advantage of the recent emerging Internet of Things (IoT) and edge computing paradigms, we propose a mobile edge computing framework that enables a holistic strategy to optimize individual vehicles' driving speed at signalized intersections. The optimization aims to mitigate the stop-and-go traffic pattern and its undesirable consequences in urban transportation systems. The framework employs a cyberinfrastructure that integrates real-time traffic and signal-timing information from IoT-connected signal controllers and sensors. The information is then broadcasted to speed control algorithms deployed on drivers' smartphones to provide energy-efficient speed advisory. Our methodology proposes a Publish/Subscribe (Pub/Sub)-based Vehicle to Infrastructure (V2I) communication pattern to minimize latency. We develop an ad-hoc mobile computing environment that converts drivers' smartphones into edge devices to enable Cyber-physical control for speed optimization in an urban traffic corridor. The paper presents the design and implementation of the proposed framework and demonstrates its usability, utility, and environmental benefits to urban systems through user surveys, lab tests, and simulations.**

I. Introduction

In an urban transportation system, stop-and-go traffic refers to the vehicle movement pattern that involves repeated deceleration–acceleration cycles and vehicle idling, which is known as traffic oscillation [1, 2]. This pattern often results from the rapid increase in automobiles and their usages, which exceed the saturation point of urban transportation infrastructure [3]. Unlike the free flow condition on highways, where most vehicles travel at a steady speed, the stop-and-go traffic pattern often cause interrupted and congested flow conditions with heavy traffic volume, bumper-to-bumper driving, and low speed in urban traffic corridors [4, 5]. These flow conditions are responsible for delayed commuting time, unnecessary fuel consumption, and excessive on-road emissions of carbon and pollutant in many cities [6, 7], incurring the estimated additional economic cost up to $124 billion per year across the United States [8]. The stop-and-go traffic arises on urban roads due to various factors, including lane merges, aggressive driving behaviors, and infrastructure bottlenecks [9, 3]. This traffic pattern is particularly prevalent at signalized intersections in urban traffic corridors where the high vehicular density often exceeds the capacity of traffic signal controls. Past studies demonstrated that nearly 50% of the vehicle energy is consumed for accelerating the vehicle back to free flow speed at urban intersections [10]. Subsequently, reducing the braking and accelerations associated with the stop-and-go patterns could potentially lower vehicle fuel consumption and emissions in urban areas [2, 6].

As a part of ongoing efforts toward smart and sustainable cities, Intelligent Transportation Systems (ITS) are deemed critical elements of smart approaches to improve urban mobility without the need to costly increase or retrofit the existing infrastructure [11]. These smart approaches aim at optimizing the network performance index, which reflects the reduction of traffic congestion in the form of minimizing total travel time and maximizing the mean speed [11]. They can identify transportation bottlenecks, optimize traffic controls and vehicle driving behaviors, and reroute traffic flow [12, 13].

Based on the emerging IoT-connected infrastructure and connected vehicle technologies, many past studies have focused on optimizing traffic control to reduce congestion at signalized intersections [14, 15]. These studies have developed optimization strategies using both traffic simulation and artificial intelligence-based solutions. As examples, many strategies employ traffic signal timing optimization algorithms to

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optimize traffic light controls, such as the cycle time and the split time [16, 17, 18]. Other strategies develop vehicle speed optimization algorithms that utilize real-time signal timing information to optimize individual vehicles' arrival time, engine power, and brake force to minimize their wait time and fuel consumption [19, 20, 21, 22].

A. Motivation

As the effectiveness of these optimization strategies has been proven through traffic simulations, laboratory experiments, and field tests, there is a technical need to wirelessly connect vehicles and deliver the optimization strategies (i.e., driving speed advisory) as a intelligent transportation service to these vehicles in a real-world urban transportation system [23, 24]. Despite the effectiveness of many existing Information and Communications Technologies (ICT) that promote Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Everything (V2X) communication, the deployment and scalability of these technologies are often limited by their hardware requirements. Many existing connected vehicle applications that rely on the Dedicated Short-Range Communications (DSRC) protocol often require the installation of specialized onboard hardware (e.g., advanced vehicle-sensors and onboard computers), which are not readily deployable to most traditional vehicles.

In this regard, developing a deployable, low-latency, and low-cost communication and computing media that can enable the cyber-physical integration between individual vehicles with transportation infrastructure (e.g., signal controllers) and the execution of real-time traffic optimization algorithms remains a critical task [25].

B. Related Work

The recent advancement in the wireless network, mobile computing, and sensing technologies has transformed smartphones into IoT-connected platforms to enable crowdsourcing, augmented reality, and geospatial computing for a variety of research and educational applications [26, 27, 28, 29]. Equipped with a number of built-in sensors that measure geo-location, acceleration, orientation, and angular velocity, smartphones can provide the essential hardware to connect automobiles to the mobile network, generating new opportunities for a variety of mobile applications (i.e., smartphone apps) for supporting the smart management of urban mobility and transportation systems [30, 24, 31]. As smartphone penetration increases across the world, mobile apps are becoming a critical onboard client in developing the Internet of vehicles (IoV) network. They have played critical roles in ad-hoc sensing, guidance and information sharing, and facilitating human-computer interaction in the recent ITS development. From the technical perspective, many of these mobile apps can track and analyze the spatial and temporal distribution of human mobility (e.g., pedestrian, bike, and automobiles) [32], collect and share travel-related information (e.g., traffic condition, route calculation, parking availability) [33, 34], and support transportation assets management [35, 26]. Following the vision of the U.S. Department of Transportation (USDOT)'s Dynamic Mobility Applications (DMA) Program [36], many past studies have developed mobile apps to connect vehicles to the network and deliver intelligent transportation services to individual transport.

In the mobility sensing sector, [37] presented the design and development of a mobile platform that integrate various wearable devices to facilitate the communication, coordination, and collaboration between different actors (e.g., freight drivers, customers, and courier distributions) in urban logistic operations. [38] introduced a user-friendly, open-source Android smartphone application to collect travel behavior data. The mobile app is developed as one of the efforts for enabling advanced traveler information systems (EnableATIS) [39]. It combines GPS-based sensing with advanced statistical and machine learning techniques to automate the detection, identification, and attributes summary of daily activity and travel episodes (e.g., travel mod, position, and route data). The app also incorporates survey techniques to allow users to input contextual information on their travel activities and episodes. [40] developed a mobile app to connect pedestrians to transportation infrastructure and nearby connected vehicles as a component of the Multi-Modal Intelligent Traffic Signal System (MMITSS). The app is designed to help visually impaired pedestrians safely navigate the crosswalk at signalized intersections, providing auditory and haptic feedback to allow users to send a call for service, align with the crosswalk, and learn about the traffic light countdown. [41] utilized a mobile app to incentivize trained divers to report road conditions to local transportation management agencies, which complements information gathered by field crews. The app is developed as part of the Utah DOT Weather Responsive Traveler Information System. The USDOT's Applications for the Environment: Real-Time Information Synthesis (AERIS) program also proposed the use of smartphones to support connected eco-driving through gamified/incentives-Based mobile applications [36]. The mobile app allows vehicular systems to sense its operating condition and communicate information about the vehicle's performance directly to the driver using the dashboard or wirelessly to a smartphone. The communication can send drivers eco-driving recommendations and post-trip feedback on their driving behavior. The feedback aims to help drivers to adapt their driving behavior to the vehicle's characteristics to promote energy-efficient driving techniques.

In the mobility management sectors, many mobile apps are developed to optimize the urban traffic and transportation system, with the goal of optimizing infrastructure usage and traffic safety. [34] developed a smartphone app to enable "smart parking" in an urban environment. The app can assign and reserve optimal parking spots for a vehicle based on its combined proximity to destination and parking cost and ensure the efficient allocation of the overall parking capacity through Mixed Integer Linear Program (MILP) optimization. [42] created a mobile app to provide drivers with speed limit advice and warnings. The app is developed as an advisory Intelligent Speed Assistance (ISA) application to reduce drivers' speeding behavior and improve traffic safety in the urban environment.

C. Knowledge Gaps

Despite the success and usefulness of these previous studies, the usage of mobile apps for mitigating traffic congestion at signalized intersections is still rare. A few studies have tested various traffic optimization strategies that optimize vehicle speed and signal timing plans at traffic lights to reduce the stop-and-go traffic pattern, while these tests are only conducted in traffic simulation environments [43, 44]. Many of the recent optimization strategies requires V2I and V2V communication capability to produce timely and accurate speed advisory based on the surrounding traffic and signal light status. In this setting, there is a need for an integrated mobile computing application that can (1) connect vehicles with the traffic infrastructure and (2) deploy and deliver these simulation and machine learning-based traffic optimization strategies to real-world vehicles. The proposed application creates opportunity to conduct field tests of optimization strategies created through simulation in an urban environment. The platform also servers as a media to enable the web deliver scientific outputs to city residences' daily life for a more optimized mobility.

In addition, most of the existing mobile apps are developed as crowd-sourcing, sensing, and information platforms without ad-hoc computing capability. Currently, mobile apps that are developed as a V2I communication client of a cyber-physical system for holistic traffic optimization, which considers the signal light's green window and overall traffic conditions at multiple intersections, do not exist. As running vehicle speed optimization algorithms for a large number of vehicles can be a computation-intensive task using the traditional server-client paradigm, there is a technical need to develop a mobile computing strategy that can distribute the computation load from the sever to edge devices deployed on individual vehicles.

D. Key Contributions

In this paper, we present a mobile edge computing framework that leverages the capacity of modern wireless networks, as well as the computing power of cloud-based cyberinfrastructure and modern edge devices (e.g., smartphones and tablets), to deliver complex traffic optimization strategies through the concept of Internet of vehicles (IoV) network and Cyber-Physical System (CPS). Our framework adopts a multi-tier architectural pattern to seamlessly integrate a two-way Dynamic Messaging System (DMS) that broadcasts signal timing information with a mobile app deployed as an onboard unit in individual vehicles to provide real-time intelligent speed assistance to help drivers reduce their stop-and-go driving pattern. Through the proposed framework, the computation load is distributed between the DMS enabled through a cloud-based cyberinfrastructure and the mobile app deployed on drivers' edge devices. The DMS is responsible for collecting real-time signal timing information and traffic condition (e.g., speed and volume) for each signal phase from IoT-connect traffic light controllers and camera sensors deployed at multiple topologically connected intersections across an urban traffic corridor. Afterward, the large volume of unstructured signal timing information and traffic condition data is processed through the DMS and disseminated to vehicles that are approaching the intersections from specific directions and lanes using adaptive geofencing techniques. On the vehicle end, the mobile app takes advantage of the smartphone's wireless network and sensing capability to selectively receive information from the DMS and integrate signal data with the vehicle's driving information sensed through the smartphone's mobile sensors. The app then enables an ad-hoc computing environment to execute the Distributed Queue-Aware Eco-Approach Strategies (DQAEAS) and Bilinear Signal Control Algorithm using the combined signal-vehicle information to produce intelligent speed advisory in real-time.

Our approach and methodology differ from the previous studies and DMA developments in the following ways:

1) An integrated cyber-physical integration between the vehicles, infrastructure, and computing-based optimization strategy in real-time.
2) A cloud-based cyberinfrastructure to optimize the data assembly from IoT-connect infrastructure and V2I communication using a spatially and temporally partitioned data management techniques.
3) An adaptive software suite and architecture to integrate traffic optimization algorithms into cross-platform mobile apps that are compatible with iOS and Android devices and the web browser environment.

Our mobile app adopts an audio-visual combined technique to facilitate the Human-computer interaction between the driver and the speed advisory. The app is developed with light-weight, low-cost, and open-source technologies, and has been tested through real-vehicle experiments conducted in a Connected and Automated Vehicle Environment (CAVE) laboratory.

This paper presents the proposed mobile computing framework's design, implementation, and user survey. We developed several case studies in simulation and laboratory environments and on smartphones with different operating systems and hardware specifications to verify our solution's communication latency. We conducted a preliminary test drive on a physical vehicle deployed in a VISSIM simulation-powered CAVE laboratory, which is developed as a digital twin to mirror the Shallowford road traffic corridor in Chattanooga, Tennessee. Through the simulation-based test drive, we aim to demonstrate the usability of our mobile app and quantitatively estimate the environmental and socioeconomic benefits of using our solution on individual and multiple vehicles in the simulated urban transportation system. These benefits are characterized by the reduction in congestion (average wait time), fuel consumption, and emissions and are analyzed under scenarios with different penetration rates.

II. Methods

The section justifies the conceptual design of our method, lists the design requirements for the technical implementation, and introduces three major components of our framework. These components include the vehicle speed optimization algorithm, data sources, and V2I communication.

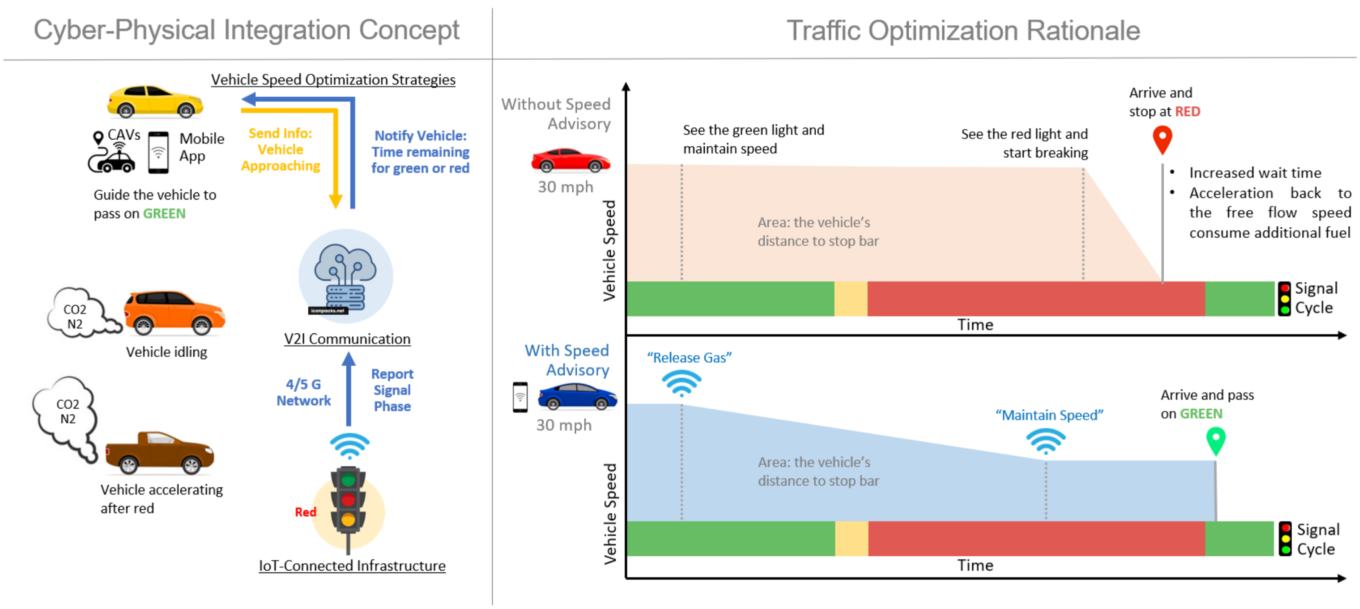

Fig. 1: The concept of cyber-physical integration for vehicle driving speed optimization

A. Conceptual Design

At the methodological level, we devised a novel pipeline that utilize the concept of Cyber-physical control to promote eco-driving behaviors of physical vehicles at multiple urban intersections by delivering computational and data-driven optimization strategy to drivers smartphones using wireless network. The pipeline defines three major components that include (1) onboard speed optimization strategy, (2) V2I communication, and (3) IoT-connected transportation infrastructure, such as traffic light controllers and CCTV (closed-circuit television) cameras. The overall conceptual design and rationale of our traffic optimization strategy is depicted in Figure 1.

The onboard speed optimization strategy is deployed on a mobile app to provide drivers with real-time speed advisory. This study uses the DQAEAS and bilinear signal control algorithm as our speed optimization strategy. The mobile app is connected to the wireless network. It estimates the vehicle driving conditions using smartphone sensors and retrieves the traffic condition and signal timing information at the approaching intersection through the V2I communication. After the information is combined, the speed optimization algorithms are executed in real-time within the mobile app to generate intelligent speed advisory at a one-second resolution. Using both the signal timing and mobile-sensed vehicle driving information (e.g., velocity, acceleration, and distance to stop bars), the speed control algorithm can calculate an optimal vehicle speed trajectory that employs coasting whenever possible for decelerations to reduce energy consumption and smooth traffic flow. Details regarding the DQAEAS and bilinear signal control algorithm, as well as their input requirements, are explained in Subsection II-D and [22]. Additionally, the mobile app is also responsible for the identification of the exact signal controller that is responsible for the light change on the vehicle's route. Subsequently, we developed a geoprocessing pipeline that can automate the generation of the intersection layout and detection zones for individual lanes and map individual vehicles within a specific detection zone to its corresponding signal controller and phase through geofencing technique.

The V2I communication is enabled through our DMS deployed on a cloud-based cyberinfrastructure. The DMS is responsible for creating a direct communication with the mobile app. It retrieves signal timing information (e.g., the green window for individual traffic phases) and traffic data (e.g., speed, volume, and turn movement) from IoT-connected infrastructure. After the information retrieval and integration, the DMS creates a broadcast channel for individual signal phases at each traffic intersection. When an approaching vehicle is mapped to a specific controller, the mobile app on vehicles will be automatically connected to the targeted signal broadcast channel and receive the most updated signal timing and traffic information. Our DMS adopts Pub/Sub communication paradigm to ensure real-time two-way communication between the vehicle and signal controller within each signal broadcast channel.

The IoT-connected infrastructure component entails signal light controllers and CCTV cameras deployed at each urban intersections. These infrastructure are connected to an edge server following the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP) standard. In our framework, the DMS is connected to the NTCIP edge server for traffic and signal information discovery, management, and retrieval.

B. Design Requirements

The proposed mobile computing framework needs to fulfill a list of essential technical requirements to ensure a smooth and reliable V2I communications for providing accurate intelligent speed advisory. These requirements are as the following:

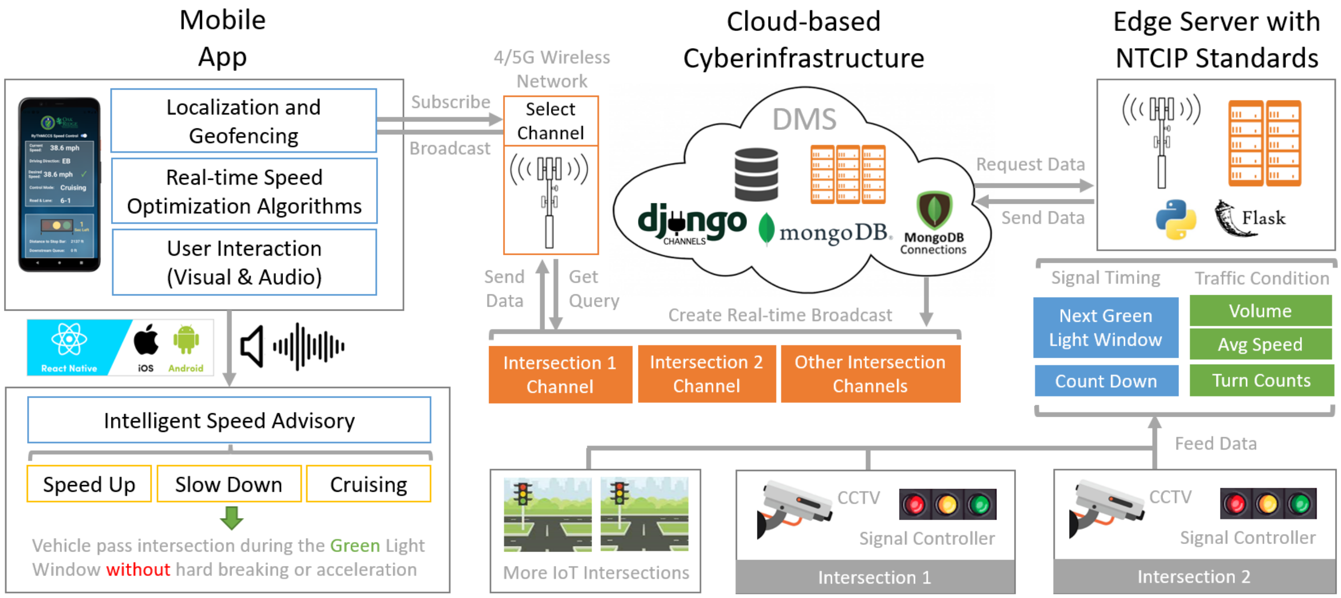

Fig. 2: The concept of cyber-physical integration for vehicle driving speed optimization

1) Vehicle localization: the mobile app should have the spatial analytical capability to detect vehicles near signalized intersection using geographic data collected from the smartphone sensors. The app should be able to map vehicles to their occupying lanes and related signal controllers.
2) Ad-hoc computing capability: the mobile computing framework should be able to balance the computation load between the server and edge devices. On the edge device, the mobile app should be able to ingest the real-time input data and execute the speed control algorithm at one-second resolution.
3) System interoperability: it should adopt industry standards and conventions on system design to ensure its modularity and to enable interfacing with other smart city and mobility applications (e.g., digital twins, web apps, and domain-models).
4) Low communication latency: the V2I communication should have a minimum delay that allows the real-time execution of the speed optimization algorithm at one-second resolution.
5) Cyber-security aspect: the V2I communication between the mobile app and DMS should be protected to avoid privacy leakage and cyber-attack on transportation infrastructure (traffic light controllers and CCTV cameras).
6) User interaction for safe driving: the mobile app should adopt intuitive and explicit user interaction techniques to create timely and easy-to-understand communication between the speed advisor and the driver. The communication should be in both visual and audio form to avoid the distraction of the driver.

C. Architecture Design

We propose a multi-tier design for our mobile computing framework based on the design requirements identified in II-B. The overall design of the framework is depicted in Figure 2. There are three tiers defined in our framework, namely mobile edge, cloud-based cyberinfrastructure, and NTCIP edge servers. These tiers distribute information and computation at different levels to enable the time-critical speed advisory on many vehicles in large urban corridors.

D. Speed Optimization on Mobile App

The mobile app is deployed on the driver's edge devices and is responsible for providing real-time speed advisory and communicating the advisory with the driver. There are three major components in the mobile app, which include (1) localization and geofencing, (2) real-time speed optimization algorithms, and (3) user interaction.

1) Localization and Geofencing: The localization and geofencing component is developed to help the mobile app measures the geographic location of the vehicle using smartphone sensors and apply geofencing techniques to connect the vehicle with the corresponding traffic light controller. Vehicle location sensing is activated when the speed advisory function is enabled on the app under an approved location-sharing permission from the mobile device. The sensing produces the vehicle's geographic location from GPS, as well as the driving direction detected through the gyroscope sensor. Both sensing results are created at the one-second interval and are used in the geofencing technique.

Our geofencing technique defines the lane configuration and spatial layouts at each signalized intersection. The lane configuration describes the number and type (e.g., left-protected turns, straight, and right turns) in each driving direction (e.g., northbound or eastbound) at individual intersections. This lane-specific information can be either manually defined or automatically retrieved from the metadata provided by traffic sensors and CCTV cameras deployed at the intersection. In this study, we derive the lane configuration from the metadata of the GRIDSMART traffic camera systems, which are available in many major cities in Tennessee [45].

On top of the lane information, we can delineate the spatial extents of individual lanes by developing an automated geo-processing pipeline. The pipeline design is illustrated in Figure 3. The pipeline takes three inputs that include (1) lane configuration, (2) a generic network of road centerlines as a GIS shapefile, and (3) pre-defined intersection lane geometry based on the design manual.

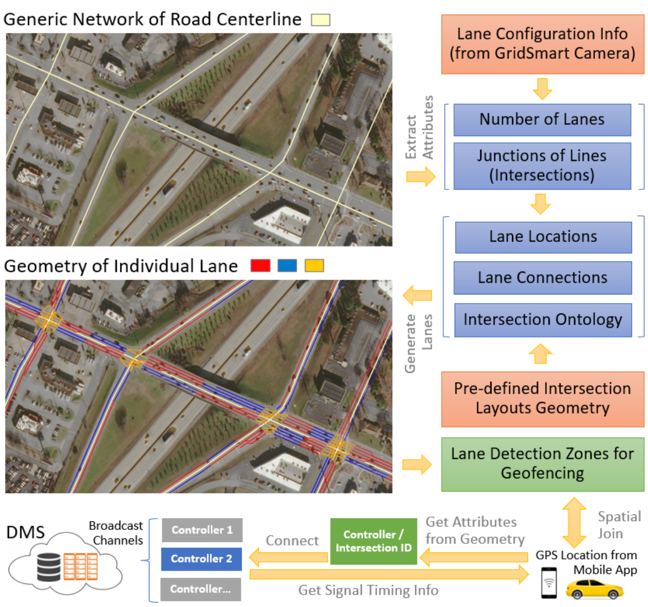

Fig. 3: An automated pipeline for creating lane detection zone to enable geofencing-based vehicle detection at intersections.

By extracting basic intersection attributes from the road centerline data, our pipeline could determine the number of lanes and their locations on roads that connect intersections. The pipeline then merges this road information with the lane configuration data to define transition areas between the road and the intersections (e.g., the start of a highway ramp or right-protected turn). Within the intersection area, the pipeline combines lane configurations and lane location data with predefined intersection lane geometry data to dynamically generate intersection layouts (e.g., location of the stop bar and connectivity between lanes in different driving directions). The generation is guided by intersection ontology that is created based on traffic rules and transportation assets design guidelines (e.g., the width of a lane location of a stop bar). Through the above-mentioned procedures, the pipeline could generate the geometry of individual lanes at an intersection, which could later be used to generate the spatial extent of each lane. The lane spatial extent provides the basic boundary for the geofencing techniques, which could detect entering vehicles. The detection is made when a vehicle's GPS location overlaps with the detection zone, and its driving direction measured through the mobile gyroscope sensors matches the direction of the zone's lane direction.

After an approaching vehicle is detected through the geofencing techniques, the pipeline maps the vehicle to the corresponding intersection ID and lane ID of the vehicle's entering detection zone. These IDs are connected to the ID of the traffic light controller that is responsible for the signal timing of the lane where vehicle is driving. Using the traffic controller and intersection ID, the mobile app could seamlessly connect to the correct broadcasting channel to receive the real-time signal timing information, which serves as a primary input for the speed control algorithms (described in II-D2).

The geo-processing pipeline is implemented using Node.js and Turf.js library to ensure that the pipeline can be executed both on the server-side and client-side. The creation of the lane detection zone is executed on the server-side through the cloud-based cyberinfrastructure, while the geofencing and detection of vehicle is executed on the mobile app developed using React Native, a JavaScript-based native mobile app framework. These implementations can fulfil the first design requirement for enabling vehicle localization.

2) Speed Control Algorithm: We integrated the Distributed Queue-Aware Eco-Approach Strategies (DQAEAS) and bilinear signal control algorithm into our mobile app as the speed control algorithms. More details regarding the DQAEAS and bilinear signal control algrithom are provided in [22]. When deployed on our mobile app, these algorithms take a list of inputs that are measured or derived from the smartphone's sensors, and sent by the signal controller through the DMS. The DQAEAS algorithm is executed at every second interval and requires some of its input at the second resolution.

The inputs measured through the mobile sensors are used to describe the vehicles' driving conditions. These inputs include the vehicle's geographic location, acceleration, and orientation of the smartphone. The derived input is the vehicle's driving speed, which can be calculated using its geographic location and acceleration. The accuracy and feasibility of the smartphone-based GPS speedometer are analyzed by [46]. In our mobile app, we use acceleration measurements to validate the driving speed derived from the GPS, as both measurements are collected at a one-second resolution.

The inputs acquired from the DMS describe the signal timing and traffic condition at the intersection. They are retrieved either from the traffic signal controller or the CCTV camera. Inputs collected from the traffic signal controller include the current signal state, the remaining time of the current state, and the next signal phases. The inputs from the CCTV describe the average traffic volume and speed at the intersection. Based on the detection zone entered by the vehicle, the algorithm also use the topology of the road network to retrieve the signal state

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3) User Interactions: We aim to make the interaction between the driver and mobile minimum but effective to avoid potential distraction during the driving. Both visual and audio-based communication techniques are applied in our mobile app to inform the drivers on the most updated speed advisory. The

Fig. 4: An automated pipeline for creating lane detection zone to enable geofencing-based vehicle detection at intersections.

visual-based communication is enabled through a graphical user interface depicted in Figure 4. The user interface displays both the vehicle's driving condition and speed advisory results. The vehicle's driving condition includes the vehicle's current driving speed, which is estimated using GPS, and the intersection and road name that is identified using the geo-fencing technique. The speed advisory results are displayed using a traffic light visualization and a color-coded timeline for the countdown. Two other parameters that are displayed in the interface include the vehicle's distance to the stop bar and queue length estimated by the speed control algorithms. The countdown represents the remaining time of the current signal state (e.g., green, red, and yellow). The audio interaction is enabled through voice assistance, which speaks out the speed advisory to the driver.

The driver can use a single button to switch on and off the speed advisory. Once the speed advisory is activated, all the processes, which conduct geo-fencing, receive signal messages, and calculate speed advisory, are fully automated and do not require any inputs or interactions from the driver.

4) Mobile App Implementation: The mobile app is implemented using React Native [47], an inter-operable software framework that utilizes JavaScript and the web browser-based React framework for developing native mobile apps that can run on multiple platforms, which include Android and iOS. The speed control algorithm was originally implemented using Python and was converted to JavaScript to be integrated into the React Native framework. The sensing compatibility of the mobile app is implemented using the React Native Sensors and Expo Sensor library, enabling both the GPS sensor, accelerometer for vehicle acceleration measurement, and gyroscope to determine the vehicle's driving direction. The geo-fencing technique is implemented using Turf.js, a JavaScript library that can perform spatial analytics and be integrated into the mobile app framework. The lane detection zones are partitioned by regions and sent by the DMS through HTTP requests based on the vehicles' geographic locations. The geometry of these detection zones is received by the mobile app as a GeoJSON file, which can be directly inputted to Turf.js.

We also employed the React Native Expo framework [48] for fast deployment and testing of our mobile app. The framework can bootstrap the developmental code of the mobile app and send it to any testing device with the Expo mobile app through a proxy network. The code of the app is then compiled on the testing devices for testing and experimental purposes.

E. Cloud-based Cyberinfrastructure

We developed a DMS to enable real-time V2I communication. The DMS is developed using a cloud-based server application with the capability of creating long-running connections between the mobile client and the server. Examples of these connections include WebSockets and MQTT (IoT), which are communication protocols based on publish-subscribe patterns. The advantage of these patterns is their capability to create a real-time two-way messaging channel through a continuous connection. Our DMS is able to create multiple messaging channels that are directly connected to the edge servers that provide signal timing information from traffic light controllers. Each channel is assigned to a single signal controller, which controls the signal timing in a specific lane at the intersection. The ID of the messaging channel is mapped to the ID of the controller, which is associated with the name of its controlling intersection and lane. Once the mobile app has identified the lane and controller ID the vehicle ID is approaching through the geofencing technique, the app will use the controller ID to subscribe to the corresponding channel. This subscription allows the vehicle to receive the signal timing information that is directly sent through the corresponding edge server. The subscription to the channel will be kept while the vehicle is traveling through the lane detection zone to allow the mobile app continuously receive signal timing updates. The subscription will be closed when the vehicle leaves the lane detection zone or enters another detection zone.

The DMS is implemented using the python Django framework with a Channels extension library. The Django framework is used to create restful APIs to send the detection zone geometries to the mobile app based on the vehicle's location. The Channels library allows the Django framework to set up WebSockets, which is used to create the V2I broadcast channels.

F. Edge Server

Edge servers are powerful computing and data processing devices physically located near the system or application where data are generated or stored. In our computing framework, edge servers are the computers that are directly connected to the traffic signal controllers through the the National Transportation Communications for ITS (Intelligent Transportation Systems) Protocol. The edge servers used in this study are maintained and managed at the Chattanooga Department of Transportation. The edge servers directly subscribed to the broadcast channel enabled through the DMS, allowing the mobile app to receive the most updated signal timing information with minimum latency, which are tested through field studies in Section III-A.

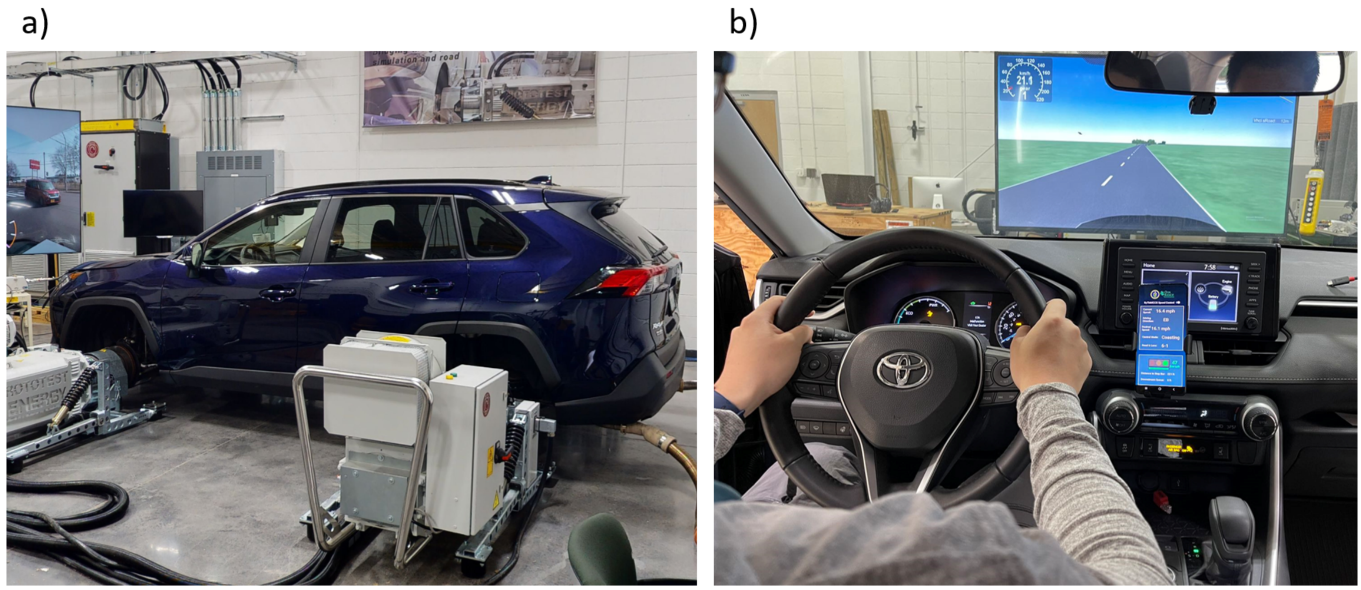

Fig. 5: The concept of cyber-physical integration for vehicle driving speed optimization

The connection between the DMS and the edge server is configured to be single-directional so that the traffic optimization algorithms can only receive information from the controller but not directly alter the signal phases at traffic controllers. This setting aims to protect transportation infrastructure from cyber-attacks.

III. Results

We devise a series of case studies through a simulation-driven CAVE lab driving experiment and field communication test to evaluate the performance and feasibility of our mobile computing framework from a variety of aspects. These aspects include (1) the usefulness of the mobile app, (2) the urban and environmental benefits from the speed advisory algorithms, and (3) the delay of V2I communication in real-time in real urban environments.

A. CAVE Lab Experiment and Utility Evaluation

We conduct a driving experiment to test our mobile app in the ORNL's CAVE laboratory. CAVE stands for "Connected and Automated Vehicle Environment". It is a hardware proving ground that is developed to evaluate intelligent mobility solutions and acquire real vehicle performance data through an integrated virtual and physical environment. In the environment, a real-world physical vehicle is deployed on an advanced steerable chassis dynamometer and is placed in front of an immersive display that presents virtual on-road scenarios rendered through a driving simulator and background traffic simulation software deployed on a high-performance computing device. There are many existing driving simulators, such as CARLA and IPG CarMaker, that can be connected to the CAVE lab setting to visually render a 3D realistic on-road scenario (with roads, intersections, and traffic intersections). The background traffic simulation software is used to define the behaviors of other dynamic traffic objects (e.g., traffic lights and other vehicles) in the on-road scenario and relies on the VISSIM software in our experiment. In order to increase the realism of the virtual driving experiences, the dynamometer can record vehicle driving conditions and drivers' behaviors and provide feedback to the background traffic simulation software to alter the behaviors of background traffic objects and interact with the test driver's actions and performances. The hardware configuration of the CAVE lab is illustrated in Figure 5a.

In this setting, the CAVE environment provides an efficient way to allow us to test our mobile app's performance and utility on a real-world smartphone and through the test drive in a physical vehicle. In the experiment, we used a Samsung galaxy s21 with a 4G mobile network to host our mobile app. The vehicle used for the experiment is a traditional SUV deployed on the dynamometer. The experimental setup is depicted in Figure 5b. Several VISSIM scenarios within the Shallowford road traffic corridor in Chattanooga have been used to render the virtual test drive during the experiments.

In order to assess the design and usefulness of our mobile app, we invited a panel of 15 observers consisting of both experts and non-experts to speculate on the test drive using the mobile app. Among the panelists, 10 observers are transportation and urban scientists from the National Transportation Research Center (NTRC). The remaining observers do not have any transportation-related technical backgrounds. An evaluative survey was sent to the invited observers after the experiment to (1) collect qualitative feedback on the usefulness and intuitiveness of the mobile app's interface and its visual and audio speed advisory, (2) learn if there are any traffic safety concerns related to the use of the mobile app and its speed advisory feature, and (3) identify potential improvements for daily-life use in large urban areas.

All/most observers commented positively on the usefulness of the mobile app from the following perspective:

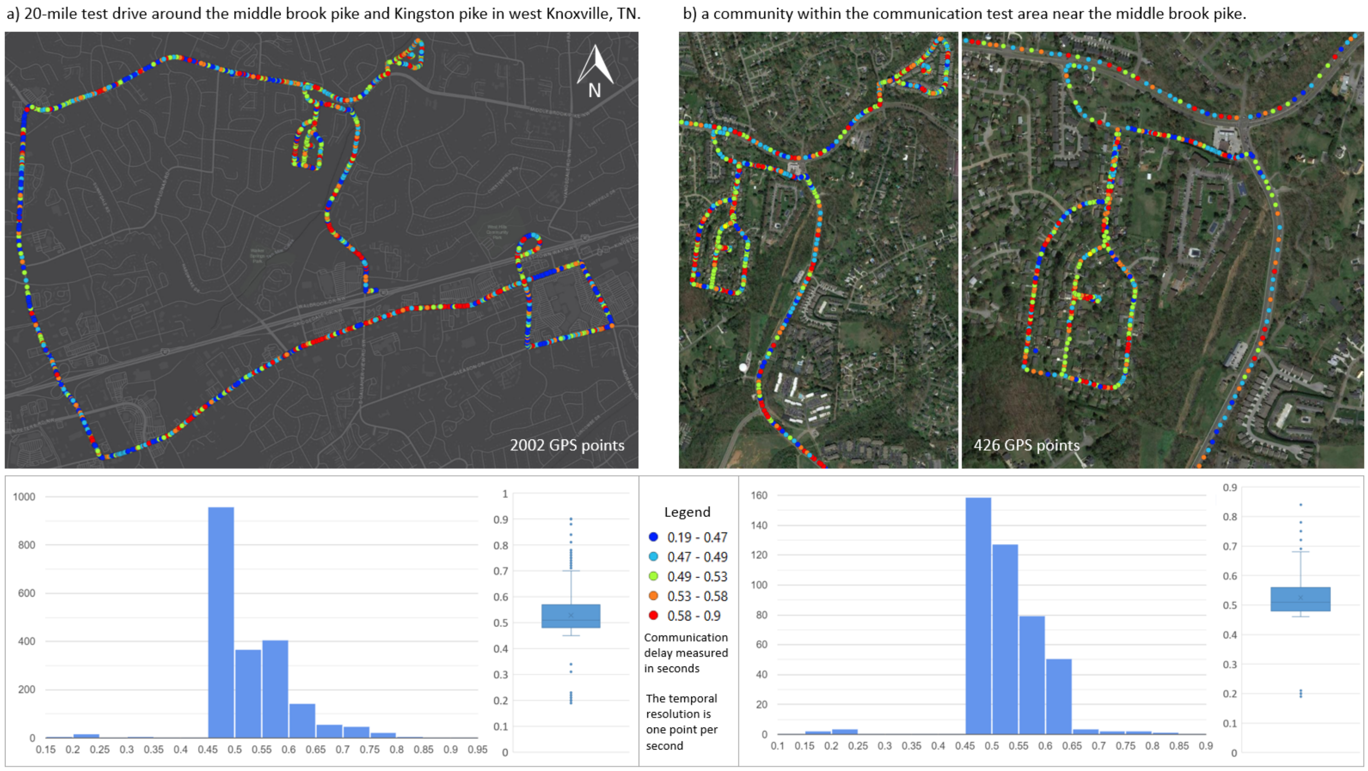

Fig. 6: Communication delay tests are conducted through a 20-mile drive in west Knoxville in Tennessee: (a) regional result consisting of 2002 GPS points, and (b) sub-region result in a community near middle brook pike consisting of 426 GPS points.

1) Comment 1 related to the usefulness of the app.
2) Comment 2 related to the usefulness of the app.
3) Comment 3 related to the usefulness of the app.

20 percent of observers addressed their concerns regarding the potential negative affects on drivers' performance. These concerns are as the following:

1) Comment 1 related to the safety concerns of the app.
2) Comment 2 related to the safety concerns of the app.
3) Comment 3 related to the safety concerns of the app.

Many observers have provided their opinion and experiences regarding the improvement of the mobile app. These advices are as the following:

1) Comment 1 related to the improvement of the app.
2) Comment 2 related to the improvement of the app.
3) Comment 3 related to the improvement of the app.

The survey is conducted as a preliminary evaluation on the utility of the mobile app and its speed advisory feature. A more sophisticated usability test and driver's behavior analysis based on formal protocols will be conducted in future in a urban environment.

B. Simulated Urban and Environmental Benefits

Along with the gamified driving simulator that visually display the on-road scenario during the CAVE Lab experiments, the background VISSIM traffic simulation software also monitors the test vehicle's condition and driving behaviors, and adjust the traffic dynamics (e.g., other vehicles' speed and driving behaviors) accordingly. changes in the traffic dynamics after the proposed speed advisory algorithm is introduced into the traffic corridor are often reflected as the reduction of the stop-and-go driving behaviors in individual vehicles, and the overall mitigation of traffic congestion at multiple signalized intersections. These changes are later analyzed using the VISSIM simulation and its expansion packages, such as the EPA's Motor Vehicle Emissions Simulator, to provide quantitative estimates of the socioeconomic and environmental benefits brought by our speed optimization strategy at different penetration rates. These benefits are characterized as (1) energy savings, and (2) reduction in carbon and pollutant emissions through vehicles' exhaust gas, and are detailed in Table 1.

jinghui Please add the simulation results that reflect the energy saving and emission reduction here in a table here

As shown in in Figure 7,

C. Field Communication Test

We conducted a field test to measure the communication delay between the mobile app and the DMS by driving a real-world vehicle in urban environment. The test aims to demonstrate the reliability and feasibility of the real-time traffic signal information delivery from the IoT-connected transportation infrastructure to the individual vehicle that uses the mobile app. A number of field tests have been conducted on urban roads in both the Anderson and Knox county in Tennessee. These tests are performed under a 4G mobile

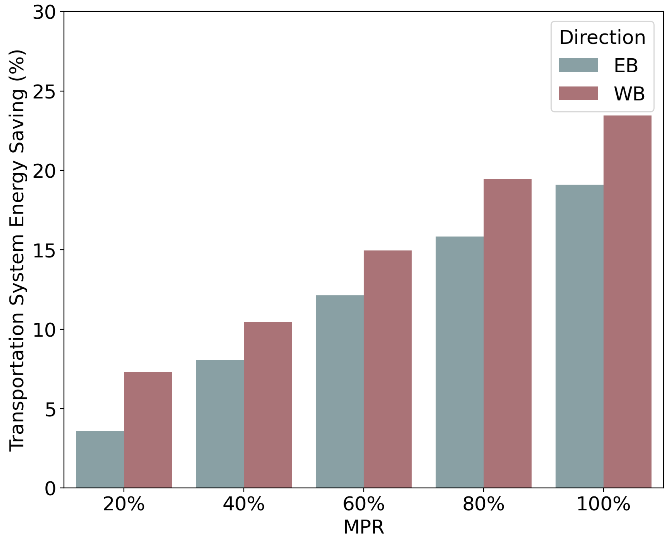

Fig. 7: The Energy Saving of Transportation System with Different MPRs of the Speed Advisory App.

network with a download speed of 115-128 Mbps and upload speed of 19.3 Mbps using two Android smartphones, including a Samsung Galaxy S21 (advanced settings) and a Samsung Galaxy A21 (basic hardware).

During these field tests, a number of emulated controllers were configured on edge servers following the same design of our computing framework. These controllers were then connected to the DMS to create their broadcasting channels and started to stream signal timing and traffic information at a 1-second interval within their channel. On the vehicle end, we activated the mobile app, which started to subscribe to different DMS channels and receive signal timing and traffic information from different emulated controllers. Once this information is received, the mobile app executes the speed optimization algorithms, which only takes less than 0.05 seconds to provide speed advisory results. Afterward, the mobile app calculated the communication delay by subtracting the information received time (using the smartphone's local time) from the information's sent time that is coded in the message by the emulated controller. The sent-time is determined using the edge server when an emulated controller broadcasts the information to a DMS channel. We synchronize the smartphone's local time and the edge server's time setting with the internet time to ensure timing consistency. The delay of each message received from the DMS is mapped to their received location using the smartphone's GPS measurements.

All the test have demonstrated that the delay between the mobile app and the emulated signal controllers is no more than 0.9 seconds, which fulfill our design requirement. We demonstrated one of the communication tests that consists of a 20-mile drive that loops the Middle Brook Pike, Cedar Bluff Road, and Kingston Pike in west Knoxville, Tennessee. The spatial mapping of the 2002 GPS points that calculates the communication delay is illustrated in Figure 6a. The result has demonstrated that most communications were completed within 0.8 seconds. We subset the result to an urban residential community near the intersection between the Cavet Station Greenway and Middle Brook Pike using 426 GPS points (as depicted in Figure 6b). The result of the subarea is similar to that of the entire 20-mile loop. Based on the result, we are confident to state that all of the 2002 V2I communication tests have fulfilled the design requirement, which ensures that the speed advisory could receive necessary input within 1 second to provide real-time speed advisory at a 1-second interval. Various fall-safe strategies have been developed to cope with the situation when the communication exceeds 1 second. These strategies include creating a local counter that uses previously received signal timing information to locally calculate the remaining time of the current signal state and its associated green window.

In this study, we do not focus on developing a methodology to retrieve accurate vehicle position and speed using smartphone sensors. We take advantage of the methods developed by previous studies to utilize the road network geometry received from online routing APIs (Application Programming Interfaces) to match and snap the smartphone GPS measurements to the vehicle's navigation route. This process can significantly reduce the uncertainty in the GPS measurement and its derived vehicle speeding using smartphone sensors. Modern smartphones also provide enhanced geolocation capabilities, which use combined features of google location service, Android location service, and WiFi and Bluetooth scanning to improve the accuracy of the GPS measurement.

IV. Conclusion

This paper presented a mobile edge computing framework to optimize traffic at signalized intersections using real-time V2I communication, vehicle speed optimization, and cyber-physical integration. Our framework consists of a mobile app, a cyberinfrastructure-enabled DMS, and edge servers that allows the real-time delivery of the signal timing information from traffic light controllers to individual vehicles that use our mobile app. The mobile app hosts a set of speed optimization strategies that utilize real-time signal timing and traffic information to provide speed advisory to help drivers avoid the stop-and-go traffic pattern in urban traffic corridors. The speed advisory gives the driver an optimal driving speed every second to ensure the vehicle can pass most of the signalized traffic intersection during the green light. A series of tests, which include a CAVE lab driving experiment, a traffic simulation-based benefit analysis, and a field communication delay test, have been conducted to prove the feasibility of our approach.

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