Resource Provisioning and Dynamic Resource Management in Intelligent Transportation Systems

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I. Introduction

Traffic congestion has adverse consequences on the safety, economy and environment. The loss of productivity due to delays stemming from traffic jams, and increased fuel consumption leads to adverse economic consequences. For example, traffic congestion alone costs the USA 2.8 billion gallons of wasted fuel and a productivity loss of 4.2 billion hours per year [1]. Different studies [2], [3] have also shown an increase in greenhouse emissions due to vehicle idling during traffic jams.

Intelligent Transportation Systems (ITS) [4] are envisioned to address the numerous challenges faced by the transportation sector. A variety of applications will be supported by ITS including safety critical applications, such as *Preventing Red Light Running* and *Safe Lane Changing*; applications for improving driving experience, such as *Dynamic Traffic Rerouting* and *Vehicle Health Monitoring*, and applications for law enforcement and disaster management, such as *Tracking Stolen Vehicles* and *Orderly Evacuation*.

Supporting the range of applications in ITS requires autonomous coordination among vehicles, sensing of traffic-related events, and dissemination of real-time alerts reliably to drivers. Supporting these capabilities is a hard problem; it requires a thorough understanding of the complexities of the ITS physics. The dominant physical artifacts of ITS are the wireless medium, mobility of vehicles, and sensing by vehicles and road-side units (RSUs).

An ITS comprises at least three types of communication networks: (1) a wireless network formed among the vehicles for vehicle-to-vehicle (V2V) communication, (2) a wireless network that involves the vehicles communicating with the road-side infrastructure (V2I), and (3) a predominantly wireline network that connects the multiple infrastructure elements. Additional networks, such as the cellular network and public Wi-Fi, can also be leveraged.

Real-timeliness and reliability of information dissemination via V2V and V2I communication is hard due to multiple challenges. Some challenges are imposed by the physics of the system including the wireless radio transceiver power, shared nature of the wireless channel, mobility of the vehicles, and density of the vehicles. Other challenges arise from the vagaries of the cyber infrastructure including behavior of protocols like 802.11 media access layer (MAC), address resolution protocol (ARP), IP addressing and routing, and retransmission and congestion control in TCP, which we discuss later. Yet another set of challenges stem from undesired human behavior (*e.g.*, undesired reaction of drivers to alerts). Finally, the constant fluctuation in resource availability and scale of the system pose significant design and operationalization challenges for ITS.

The scientific principles and engineering solutions for the design and operation of ITS must necessarily crosscut the physical, cyber and human dimensions, which makes ITS a Cyber Physical Systems (CPS) research problem.

II. ITS Design and Operationalization Challenges

Three important questions must be answered while designing and operationalizing ITS as discussed below.

(1) How to optimally provision resources? The scale of ITS systems can be extremely large, as in the national road network. Even if this system is broken down into regions on a county- or city-wide basis, yet a moderately sized metropolitan area in the USA comprises thousands of miles of roads. To support the many different applications in ITS in such a large-scale system will require an investment in several different infrastructure elements, such as road-side units (RSUs), message signs, cameras, ramp meters, and loop detectors, that will need to be strategically deployed for the maximum benefit.

To realize these benefits, a better understanding of expected traffic patterns is needed. Deployment of infrastructure elements must also account for the geographical terrain, such as hills; clutter of constructed artifacts, such as tall buildings in downtown areas; and availability of other existing means for communication, such as public Wi-Fi support or cellular towers. Capacity planning must also

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account for expected growth of a region and expected impact on the transportation sector.

To address these concerns requires engineers to develop mathematical models and simulate the transportation networks. Simulating the networks alone is not sufficient; the individual applications of ITS must also be simulated both in isolation and all together. No single simulation capability, however, exists to do all of this nor are the individual simulations computationally affordable.

(2) How to manage resources and maintain application QoS? To realize the wide range of ITS applications requires runtime infrastructure that are deeply embedded in all the artifacts of ITS, such as in the vehicles and RSUs. The runtime must support a tight integration between the physics and the cyber infrastructure. For example, in smart traffic light application, vehicles must coordinate their positions among themselves through sensing and message exchanges over the shared wireless medium; messages generated by the smart traffic light must be reliably delivered on time; sensors must continually sense the road conditions and proximity to other vehicles; and on-board cyber infrastructure must compute the right deceleration rate as well as alert the driver to take the right action.

The demand on resources, such as CPU and network, continuously fluctuates due to mobility and shared nature of the wireless medium, and the multiple different applications that contend for the shared resources. The increasing density of vehicles in an area leads to packet collisions and degradation in performance. Mobility also causes a vehicle to go out of range of equipment, such as a RSU. Signal fading and obstructed views are yet another reason for discontinuities in network access, and hence degradation in performance. ITS applications therefore need effective mechanisms for resource virtualization [5] and dynamic resource management [6] to maximize the performance of ITS applications.

The runtime substrates must also support multiple computing paradigms all at once. For example, vehicle-to-vehicle coordination in the traffic light example will require peer-to-peer models; dissemination of information to a large number of vehicles will require scalable publish/subscribe capabilities; and client-server models will be needed when vehicles register themselves with ITS services.

(3) How to deal with uncertainties arising from human factors? Humans (*e.g.*, drivers, pedestrians) are an inherent part of a transportation system, and hence their impact on ITS must be measured and accounted for both in the design and runtime artifacts. For example, drivers may decide to ignore ITS-generated alerts as in the rerouting example, which may cause undesired effects on the expected outcomes. How should the ITS design and runtime account for human behavior and the uncertainty that arises is a key question to be answered. ITS should thus provide solutions that mitigate the adverse effects of undesired human reaction.

III. Solution Approach

We are addressing the three questions raised in Section II through a three-pronged holistic approach comprising the following artifacts:

1) **Capacity planning via surrogate modeling,** which includes new design techniques and heuristics based on surrogate modeling and stochastic programming that are needed to characterize the performance of ITS CPS, which otherwise is a hard problem since testbeds are not readily available, and no single simulation tool suffices nor are the simulations computationally affordable.
2) **Middleware,** which is manifested as deeply embedded computational and communication intelligence in the form of new resource virtualization and runtime adaptation algorithms. The middleware requires sensing physical artifacts, such as wireless signal quality, and makes adjustments to provide timely and reliable information dissemination using a combination of V2V, V2I, Wi-Fi and cellular networks.
3) **Human-in-the-loop behavior models,** which deal with uncertainties arising from driver reaction to real-time alerts and autonomous control of vehicles, and resulting techniques to mitigate the impact of undesired human reaction.

Developing surrogate models for the complex ITS system follows a four step approach shown in Figure 1. The steps include (1) Modeling of system behavior along with user behavior (2) Analyzing system behavior for stability and QoS conditions, (3) Constructing an inexpensive surrogate for the expensive CPS simulation, and (4) Optimizing design variables through stochastic optimization.

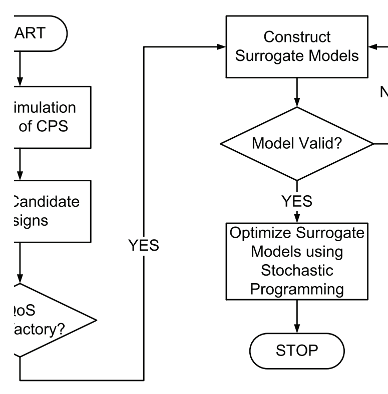

Figure 1. Four Stage Approach to Capacity Planning in ITS

In recent work [7] we have identified via simulation the time window available for a vehicle to communicate with a RSU for varying speeds and varying radio transceiver power. Since the number of combinations and parameters keeps increasing, it becomes infeasible to conduct a large number of simulations. Yet, it is necessary to identify the approximate behavior of the system despite not performing all the simulations or real-world tests.

Surrogate modeling helps in this regard as shown in Figure 2 where Gaussian Process is used over a set of training data to obtain an approximate behavior of the system. Such information is invaluable since it provides an opportunity for both capacity planning as well as runtime resource management algorithms. In this figure we show how the communication window changes with changes in radio power as well as speed.

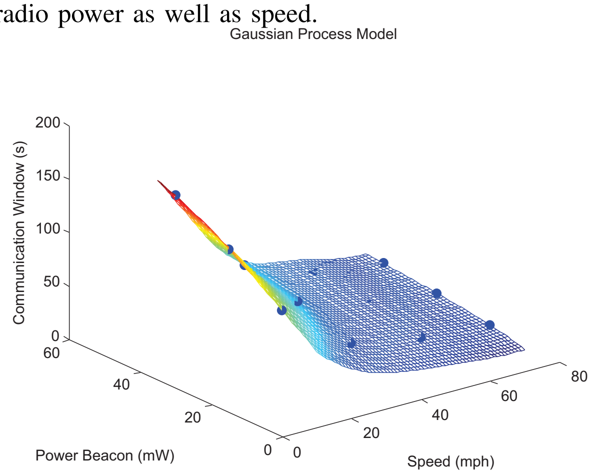

Figure 2. Surrogate Model using Gaussian Process

Our middleware solution is based on enhancements to and integration of individual middleware capabilities including real-time CORBA and lightweight CORBA Component Model, OMG Data Distribution Service, content-based publish/subscribe, and complex event processing.

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