Distributed Sensing, Communications and Control System for Enabling High Performance Vehicle Streams

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Introduction

The availability of reliable in-vehicle sensors, new wireless technologies for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication and GPS-based positioning technologies, opens the door for enhanced vehicular ***safety*** and ***efficiency***. An example is the potential to move from current standard adaptive cruise control (ACC) to cooperative adaptive cruise control (CACC) to enhance the throughput on freeways, by enabling vehicle platooning while maintaining stability and safety of the traffic stream by reducing speed variations. Some preliminary studies suggest that capacity can almost be doubled using CACC technologies by reducing the safe inter-vehicle headway. Finally, integrating CACC technologies with wireless enhanced intelligent traffic signal at freeway entries and exits can significantly improve the performance of both the freeway traffic flow and the arterial traffic.

There exist numerous technical and engineering challenges to implement a robust, fault-tolerant CACC technology. These are inter-disciplinary in nature and intersect multiple disciplines including automotive sensors, distributed sensing, control and actuation, wireless communication, communication protocols, and distributed computing, exemplifying a vehicle-centric cyber-physical system. The technical challenges in forming and controlling a platoon with tight spacing at high travel speed must confront the heterogeneity of the vehicles. Implementing a distributed control system for CACC with heterogeneous vehicles with different response functions is a challenging problem. Robust design of a control loop that relies on the DSRC/WAVE standard based wireless networking protocols itself presents many challenges - due to the strict requirements on the message delays between vehicles that must be maintained in the presence of channel impairments such as fading/Doppler shifts, network disconnections, and changing coverage. Further, the inherent variability resulting from vehicles joining and leaving the platoon will impact the ability of the wireless network to deliver the necessary control signals within the required latency bounds. Techniques such as distributed leader election and

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determining the size and membership of the platoon are important components of a potential successful CACC design.

Cyber-Physical System Architecture

In order to meet the stringent requirements of the CACC, the underlying control must be tightly integrated with the communication architecture and protocols. Figure 1 shows our proposed approach to integrate these various elements in our prototype CACC system. Integrating all the component parts to implement a CACC system that functions with heterogeneous vehicles and under different road features constitutes the fundamental challenge.

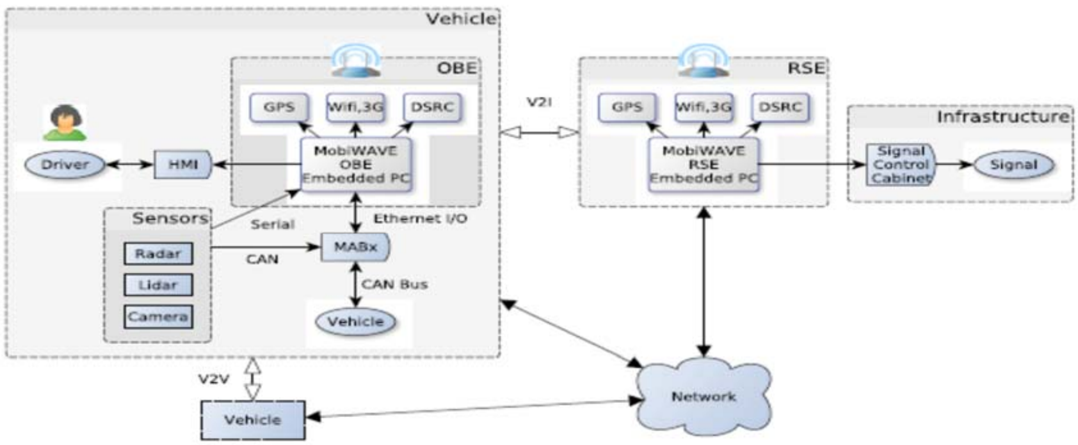

Figure 1. The Overall Communication and Control Architecture

Research and Development Challenges

Our proposed research agenda first develops a prototype system to form, maintain and dissolve high-performance vehicle platoons in special lanes under relatively homogeneous driving environment. The total productivity of a freeway, as measured by the vehicle-miles traveled per unit time and fuels consumed, critically depends on the capacity at bottlenecks: the lane-drops, merges, entrances/exits, and places where speed limits are lower. The research then addresses the problem of forming and scheduling high performance vehicle platoons in merging bottlenecks. Since the adoption of ACC is likely to be gradual, high-performance vehicle streams must co-exist with traffic that does not have ACC, greater attention is paid to developing robust communication protocols and vehicle control algorithms to enable the formation, maintenance and dissolution of high-performance vehicle streams in a heterogeneous environment with different vehicle types, highway geometry and weather conditions.

Our envisioned system will integrate WAVE/DSRC, vehicle positioning, obstacle detection, and in-vehicle processors to form opportunistically high-performance vehicle streams on-demand, particularly at merging, lane-dropping locations and on special lanes in a distributed manner. Since the formation of high-performance platoons is voluntary, a distributed algorithm is developed to initiate platoon formation in any lane, assisted by single-hop V2V communication to actuate vehicle control to maintain tight spacing between vehicles and control travel speed. Access points are installed at entrance and exit ramp locations to alert vehicles at these locations, such that platoons can be formed on both the shoulder lane and the merging/exiting lane to maximize the merging/exiting flow. The target of this envisioned system is to double the total productivity of the freeway system under reasonable amount of ACC market penetration, which is equivalent of building another interstate system with a tiny fraction of the cost.

Critical to the formation and maintenance of CACC enabled high performance vehicle streams under a heterogeneous driving environment is the tight integration of vehicle control with the communication architecture and protocols. Leveraging our expertise in wireless communications, vehicle dynamics and control, and traffic engineering, we propose several innovative solutions to enable this tight integration. To achieve ***timely, reliable*** **wireless communications**, we propose to enhance the base DCF protocol in DSRC/WAVE by introducing priority and implicit ACKs to improve multi-hop efficiency, use 2 transceivers per vehicle to ensure the timely delivery of time-sensitive messages related to vehicle safety and longitudinal control, and collect relative traffic statistics such as platoon size, speed, and number of platoons in a section of road. We also propose the novel use of *Network Coding* to achieve a more reliable DSRC/WAVE broadcast mechanism for CACC platoon control, and enable Multi-Channel Access using the concept of cognitive radio.

On the control aspects, we propose a **four-layer control architecture**, a variation of the one used in Automated Highway Systems (AHS), to handle the formation, organization, maintenance and control of tight vehicle platoons. In contrast to AHS, vehicle platoons in CACC are formed voluntarily and the membership in a platoon can be highly dynamic. We propose novel mechanisms to elect the leader of a vehicle platoon, establish the membership of the platoon, and maintain the membership of the platoon when vehicles join and leave it from time to time. While the current technology has enabled field test of CACC vehicle platoons with 0.5-1.4 second time gaps, the tested platoons are small and homogeneous. We propose nonlinear and sliding-mode control laws to take into account the nonlinear longitudinal and lateral vehicle dynamics, so that the stability of each vehicle and the entire platoon is achieved for shorter time gaps ($\leq 0.5\text{sec}$) and longer platoons, hence producing greater throughput gains. Since the total throughput of a freeway critically depends on the throughput of its bottlenecks, such as a ramp merge section, we also develop “scheduling” algorithms to enable platoon merge to double the capacity at merge bottlenecks.

We plan to conduct field experiments locally with two vehicles retrofitted to enable CACC platooning, and at Turner-Fairbanks’ Cooperative Vehicle-Highway Testbed with a larger vehicle set to evaluate the novel communication and control system concepts developed in this research. Nevertheless, both tests will only involve a limited number of vehicles that have no or limited interactions with other traffic. Our research also develops a new simulation platform that tightly integrates both traffic mobility simulation (SUMO/VISSIM) and network simulation with 802.11p stack (OMNET++), so various features of the proposed system that may not be feasible to test in the field, such as a truck merging into a platoon, can be evaluated in greater detail.