The Need for an Application-Centric Networking Paradigm for Large Scale Transportation Cyber-Physical Systems

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Introduction

The human and economic cost of transportation is a pressing global issue. Annually, around 1.2 million deaths occur on the world roads[1] (over 33000 in the US;). The inefficiency and economic cost of road transportation is also staggering; only the cost of fuel wasted in traffic reaches $88 billion a year in the US[2]. Transportation Cyber-Physical Systems (TCPS), enabled by embedding powerful computing and communication capabilities in vehicles and infrastructure, promise to considerably mitigate these issues in the coming years. While such promises are repeated frequently in various outlets, citing the potentials of systems such as automated vehicles, intelligent highways/roads, and a wholly-connected transportation system, the enormous technical challenges that lay ahead are not yet completely understood.

A critical and necessary component of TCPS is the underlying communication networking service. Communication networks provide the possibility of remote sensing/actuation and distributed control, but are prone to failure especially at large scale. The resulting **scalability issue** has been known for some time for TCPS such as cooperative vehicle safety systems (CVSS). CVSS relies on frequent vehicle state and position updates over dedicated wireless channels. Although prototypes of CVSS have been shown to work (since 2004), recent tests with 200 and 400 vehicles revealed the extent of the communication failure when a large number of vehicles are present within communication range of each other (100-1000m). The communication scalability issues translate to **unreliability** of collision warning systems; the issue would be even more serious for the automated crash avoidance systems that rely on the communication service. These communication issues are expected to only be exacerbated in networks of autonomous vehicles, since these autonomous systems are expected to require data exchange at rates that are orders of magnitude higher.

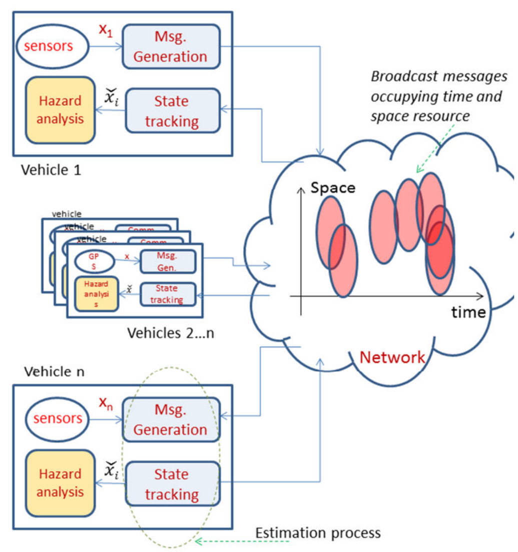

Figure 1 An abstract view of the networked vehicle safety systems (cooperative vehicle safety systems)

The approach to address these challenges has traditionally been to view the communication network component as a standalone system and treat the issue as a communication or networking problem. We argue that the communication issues in TCPS should not be approached only from a communication perspective. In a cyber-physical system (CPS), the tight coupling of computing, communication and physical aspects require solutions that recognize this coupling. We follow this line of thought and argue that communication solutions for TCPS necessitate an **application-centric paradigm;** such a paradigm should allow designing and modeling the application (incorporating physical and computing aspects of the system) and the communication system in one framework. Our evidence is the recently demonstrated advantage of application aware solutions versus purely networking solutions for CVSS.

Example of an Application Centric Networking Model

Networked vehicle safety systems such as CVSS assume that communication services are available for broadcast of vehicle state information over a distance of up to a few hundred meters. The underlying wireless technology is based on dedicated short range communication (DSRC) in the 5.9GHz band. DSRC is a local area networking technology based on 802.11 standard. The communication strategy that has been used in prototype

[1] 2010 World Health Organization report on road traffic death: http://www.who.int/gho/road_safety/mortality/en/
[2] 2009 Urban Mobility Report, published recently by the Texas Transportation Institute

CVSS systems is a simple periodic broadcast of messages at the rate of 10Hz and ranges of at least 300m (typically 500-1000meters). While prototypes have successfully demonstrated the viability of CVSS, recent tests with 400 nodes showed that the network failure prevents CVSS applications from running reliably. Figure 2 shows that in networks with a moderately high number of vehicles in range of each other (400 here), the reception rate drops below 20% even at close distances.

One approach to address this issue has been to treat the problem as a networking problem and control the load of the network (by controlling rate and range of messages) to reduce packet error rate (PER). In this approach it is hoped that the communication criterion of PER closely represents overall safety application performance. While this approach would in some cases lead to improvements, the disconnect of networking solutions from the behavior and physical dynamics of the system means that the practically achievable optimal system configurations will be almost certainly missed. Figure 3 shows an example for a case where the same PER achieves very different tracking results. On the other hand, another approach has been to consider the performance metric of “accuracy of vehicle tracking” which is a more direct metric for representing the safety application. Several recent methods have been designed based on the principle of controlling communication network to improve this metric [1]. The idea is to correlate communication with perceived vehicle tracking error in the neighborhood of a vehicle (see the architecture of Figure 4). This method is currently under study by the industry for adoption; nevertheless, an even more direct way of achieving improved performance for the collision avoidance application is desired. Metrics such as accuracy of collision warning, or estimated time to collision are such performance measures, for which there is currently no model that take into account communication complexities (except for our recent simulation models which provide a direction for future models [5]).

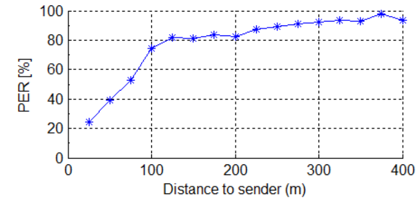

Figure 2. Without congestion mitigation techniques, DSRC networks quickly fail to deliver basic safety messages (400 vehicle scenario)

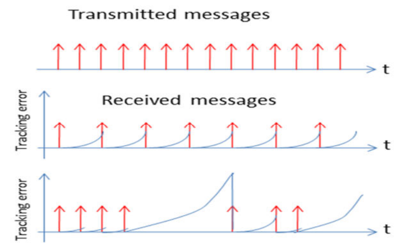

Figure 3 Purely communication metrics are not suitable for system level analysis in a TCPS

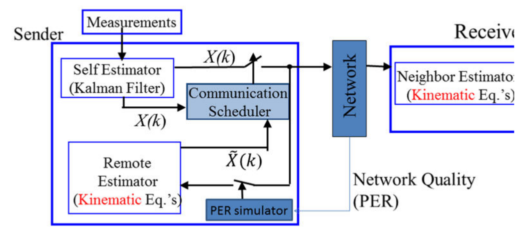

Figure 4 An Error-Dependent Application ad Network Aware Communication Logic for CVSS

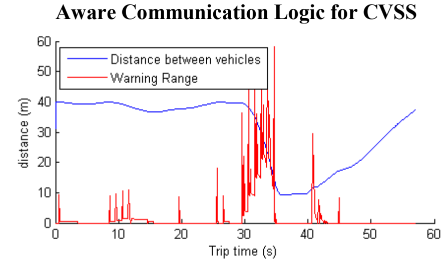

Figure 5 Example of forward collision warning range derived from co-simulator of vehicle safety and networks for CVSS.

Application Centric Networking Models: Challenges and Approaches

Despite the current efforts, there are still no application-centric networking models that can completely and effectively couple the application and communication network dynamics and control. This gap prevents optimal designs for many systems from an application perspective. Addressing this challenge requires developing methodologies and tools in three domains of co-simulation, joint hybrid modeling and joint performance characterization, as discussed below (see Figure 6 for an overall view):

1- **Co-simulation of cyber and physical domains:** for TCPS this means developing high fidelity simulation tools for the networking component and vehicle dynamics and safety applications. Co simulation provides a first step towards modeling the entire system in a single framework. Though simulation models are not completely analyzable, it is still possible to observe some of the behavioral patterns using simulation (see Figure 5 for an example)[5].

2- **Joint modeling methodology**: cyber and physical aspects of networked safety systems, similar to many other TCPS, are traditionally modeled and studied using domain specific methods. Networking component is usually modeled using queuing theory methods [3] while physical dynamics and safety applications are usually modeled using differential equations or FSM [2]. A joint modeling framework, possibly using methods based on stochastic hybrid systems (such as our recent work [5]) is an example of possible approaches. However, classic hybrid systems methodologies are inadequate to fully describe the system and allow for analysis for the purpose of optimal designs. Therefore, a new modeling methodology may still be required.

3- **Performance characterization:** The safety (and sometimes efficiency) applications of TCPS are not generally described in quantifiable terms (how to measure safety?). As a result, it is not straightforward to describe system performance metrics in an application-centric way. A method will be needed to translate network and application performance metrics to a quantifiable measure. Our recent effort in describing such measures revealed that the resulting optimal design of the system may be far from what a purely networking solution may suggest. As a result, accurate definition of performance measures for TCPS is imperative.

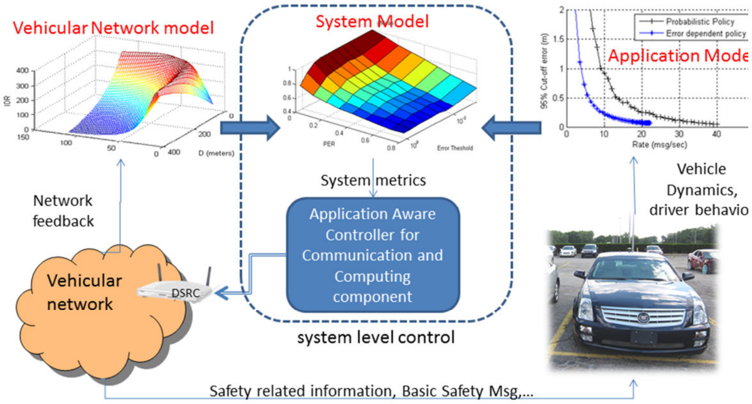

Figure 6 An example of an Application Aware Communication Controller design on data from a near crash scenario from 100-car dataset.

Concluding Remarks

The recent development of CVSS has shown that even for connected vehicle systems that use very low rate of communication, the system faces serious scalability and reliability issues in practical deployments. An effective method to alleviate these issues has been to employ more application-centric methods such as the error based and application aware adaptive congestion control schemes. The issues of scalability and unreliability are several orders of magnitude larger when data exchange between autonomous vehicles is concerned. We believe that the issue of communication is still an open problem for future TCPS and in particular for autonomous connected vehicles whose operation requires uncompromised reliability. In fact, the quality of service that is currently possible with most wireless communication techniques is not scalable to levels that can be deployable in real world scenarios of TCPS. Resolving these issues require a new look at networking models for TCPS; the application centric paradigm is a natural direction for designing such solutions.

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Yaser P. Fallah is an Assistant Professor in the Lane Dept. of Computer Science and Electrical Engineering, West Virginia University. Prior to joining WVU in 2011, he was a Research Scientist at the University of California at Berkeley, Institute of Transportation Studies (2008-2011). His current research activities, supported by industry, USDoT and USDoE grants, are in the areas of networked cyber physical systems, intelligent transportation systems, and smart energy systems. Dr. Fallah has co-chaired the technical program committees of IEEE Wireless Vehicular Communication Symp. 2011 (WiVEC 2011) and IEEE PIMRC 2011 (Intelligent Transportation Network track) conferences and is the program co-chair of IEEE WiVEC 2014.

Hariharan Krishnan is a technical fellow at General Motors Global Research and Development . He received his Ph.D. from the University of Michigan, M.S. from the University of Waterloo, and B.E. from Anna University, India. Currently, he is the thrust area lead on the GM research program on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. He works on various research projects in the area of V2X communication, including the Vehicle Safety Communications — Applications project conducted by GM, Ford, Mercedes,Toyota, and Honda under a cooperative agreement with the U.S. Department of Transportation. Prior to this, he was an assistant professor at the National University of Singapore from 1993 to 2000. He serves as an Associate Editor for the IEEE Control System Society and Transportation Research — Part C.