Taming Uncertainties in Wireless Messaging for Automotive Cyber-Physical-Systems

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1 Wireless networking for automotive CPS

Today's vehicles are much more than a mechanical device, and complex systems of sensing, computing, communication, and control are ubiquitously deployed to serve as the intelligent nerve systems of vehicles. For instance, the number of electronic control units (ECUs) is well over 70 in today's high-end vehicles, and these ECUs process up to 2,500 signals (i.e., elementary information such as vehicle speed) and support up to 500 features such as brake-by-wire and active safety [4]. The increasing number of ECUs and control systems deployed in vehicles pose significant challenges to the scalability of vehicular communication system, which is a basic element of automotive cyber-physical systems (CPS), and it has become a common practice to deploy multiple communication networks (such as CAN networks) within a single vehicle. These many vehicular networks are starting to add significant weight to vehicles and reduce gas efficiency. For instance, it has been shown that wiring harness is the heaviest, most complex, bulky, and expensive electrical component in a vehicle and it can contribute up to 50 kg to the vehicle mass [3].

To address the aforementioned challenges, wireless networks such as wireless, embedded sensor networks have been envisioned to be a basic element of future automotive CPS [3]. Besides reduced weight and thus improved gas efficiency, wireless networks also enable communication and coordination among vehicles on the road for purposes such as active safety. It is thus expected that wireless networks be ubiquitously deployed and serve as a basic element of both intra-vehicle and inter-vehicle CPS. In supporting mission-critical tasks, automotive CPS pose stringent requirements on the reliability and timeliness of wireless messaging. Nonetheless, wireless messaging is subject to the impact of inherent uncertainties and dynamics within the system itself and from the environment in automotive CPS. In what follows, we first examine the challenges that systems and environmental dynamics pose to dependable messaging in mission-critical wireless automotive CPS, then we explore research directions for addressing these challenges.

2 Complex dynamics and uncertainties in wireless automotive CPS

Within a system, wireless communication assumes complex spatial and temporal dynamics due to unpredictable channel fading, network topology constantly changes in inter-vehicle networks due to vehicle mobility, network traffic pattern can be dynamic due to event-triggered data traffic and varying applications (e.g., adaptive control logic), and application requirements on messaging quality (e.g., throughput, latency, and/or reliability) may also vary over time and across different applications. Moreover, different dynamics may well interact with one another to yield complex behavior. For instance, dynamics in network traffic pattern introduce dynamics in co-channel interference and thus dynamics in wireless link properties (e.g., reliability), which in turn affect link estimation and routing in wireless networks [5, 7].

From the environment, a wide variety of factors can affect the behavior of wireless messaging. Environmental factors such as temperature and humidity can affect wireless communication, electromechanical equipments in vehicles can create complex multipath environments, moving objects (humans in a vehicle or surrounding vehicles) may introduce unpredictable dynamics to wireless communication, co-existing wireless networks may interfere with message passing, and malicious attackers may try to jam a network.

Unlike the faults/perturbations considered in most traditional fault-tolerant systems, dynamics in wireless automotive CPS occur at multiple timescales at the same time. At longer timescales, there exist temporal link dynamics due to changing environment (e.g., temperature, humidity), long-lived traffic flows may come and go, and application QoS requirements may change. In the mean time, there exist dynamics that happen at very short timescale (e.g., in milliseconds), and they include fast channel fading, bursty traffic variation, high node mobility, and transient link perturbations due to human/object movement.

Besides differences in root-causes and frequencies, dynamics also differ in terms of controllability. Some dynamics are controllable, whereas others are uncontrollable. For instance, co-channel interference from concurrent transmitters can be controlled, so is network traffic pattern. On the other hand, many dynamics are uncontrollable, and they include dynamic wireless channel fading, interference from co-existing networks or jamming attackers, as well as unpredictable sensing events.

These multi-dimensional dynamics introduce complex uncertainties in wireless automotive CPS, and they challenge the traditional wisdom of fault-tolerant system design. To enable dependable messaging and predictable behavior of wireless automotive CPS, therefore, it is important to re-think systems design to address these complex dynamics. Given the potential resource constraints of wireless automotive CPS (e.g., limited channel bandwidth, memory, and processing power), the solutions have to be light-weight and efficient too. To this end, we explore in the next section research directions that will help lay a solid foundation in addressing these challenges of wireless automotive CPS.

3 Experimental infrastructures and holistic solutions

High-fidelity experimental infrastructures. Due to inherent uncertainties of systems and environmental dynamics as well as their interactions, empirical measurement study is crucial for understanding the complex behavior of wireless automotive CPS, for instance, for extracting models of wireless interference and for evaluating network protocols. The research community have built various wireless and sensor network testbeds such as CitySense, MoteLab, Kansei, NetEye, and TrueMobile. While these testbeds have proven instrumental in general wireless and sensor network research and education, they do not focus on supporting research and education in wireless automotive CPS and CPS in general. To facilitate wireless automotive CPS research and education, we need to develop experimental infrastructures that capture the challenges and complexities of mission-critical automotive CPS, including the interactions within the ecosystem of different wireless networks (e.g., DSRC, 802.15.4, and ultra-wideband) and different sensing substrates. To provide high-fidelity, flexible wireless automotive CPS experimental infrastructures, we need to incorporate measurement facilities with simulation/emulation tools so that we can exploit the complete spectrum of experimental design and analysis. Apart from the NSF CPS program, the NSF Global-Environment-for-Network-Innovations (GENI) initiative [2] has also been developing infrastructures for mobile, wireless network applications (including vehicular network applications). The US Department of Transportation (DOT) has built national testbeds for vehicle-infrastructure-integration, and they are in the process of phasing out the next-generation experimental infrastructures of IntelliDrive [1] and intelligent transportation system in general. Therefore, we need to explore potential synergy between the CPS program and these related programs in establishing an instrumental experimental platform for wireless automotive CPS and CPS in general.

Holistic solutions to uncertainty handling. To enable dependable messaging for wireless automotive CPS, we need to take a holistic approach to addressing the impact of complex dynamics on wireless messaging. More specifically, we need to integrate the life cycle of requirement engineering, capacity planning, protocol and system design, system analysis and performance evaluation to effectively take into account the dynamics and uncertainties in the design, analysis, and evaluation of automotive CPS.

Since sensing, computing, messaging, and control are tightly coupled in automotive CPS, it is important for experts from different disciplines to come together to thoroughly understand the problem domain, for instance, to identify the right interface among control, messaging, and sensing, and to identify the frameworks and models for system level interaction and optimization. Having the right model for the overall system architecture will enable decomposition and in turn successful composition of individual elements of the CPS in the end. To enable dependable messaging in uncertain systems and environmental settings, it is also necessary to build the modeling and analytical tools for characterizing dynamics and for understanding their impact on messaging behavior. Based on correct understanding of systems and environmental dynamics, we can examine how to design different messaging components to address these dynamics. The unique, complex dynamics and uncertainties constantly challenge the traditional wisdom in MAC, routing, and transport design, and we need to explore effective approaches to ensuring predictability, stability, and dependability of wireless messaging in the presence of dynamics and uncertainties. For instance, we need to design cognitive MAC protocols that effectively adapt to interference from both within the automotive CPS and from the environment; we also need to identify routing metrics and protocols that enable higher degree of stability in the presence of systems and environmental dynamics [7, 6]; and we also need to design mechanisms for addressing malicious attacks (e.g., jamming) to wireless messaging. For a specific set of messaging components and systems and environmental dynamics, we need to design mechanisms for capacity planning and admission control so that minimum but enough capacity margins are reserved to deal with systems and environmental dynamics and uncertainties and the network can provide predictable messaging service in the presence of dynamics and uncertainties.

In addressing the dynamics and uncertainties in wireless automotive CPS, we should also try to take advantage of the unique properties of these CPS systems. For instance, the potentially periodic, predictable control data samples may enable effective scheduling mechanisms for dealing with co-channel interference; the availability of vehicle power sources may relieve system design from severe energy constraint as seen in classical low-power sensor networks.

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Author Biography. Hongwei Zhang has extensive experience in the design, analysis, implementation, and experimentation of wireless and sensor network systems and protocols. Besides publishing in premiere journals and conferences (e.g., various ACM and IEEE transactions, MobiHoc, INFOCOM, ICNP, RTSS, PODC, and DSN), he has led and/or contributed to several wireless networked systems. He is currently working with the Detroit auto industry to develop dependable wireless networks for automotive CPS. He also co-leads the KanseiGenie project to federate autonomous wireless sensor network (WSN) testbeds in the NSF GENI program. Before the KanseiGenie project, he has developed the 145-node WSN testbed NetEye at Wayne State University, and his research results and system software have served as foundational elements of the 1,000+ nodes testbed Kansei as well as the 200-node 802.11b mesh network and the 1,200-node mote network of the DARPA field WSN project ExScal. Besides Zhang's group and his collaborators' groups, the NetEye and Kansei testbeds have been widely used by researchers from other institutions of US, China, and India. More information about his work can be found from his website at http://www.cs.wayne.edu/~hzhang/.