Predictable Messaging in Wireless Automotive CPS

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In this position paper, we first examine the challenges that systems and environmental dynamics and uncertainties pose to predictable, dependable messaging in mission-critical wireless automotive cyber-physical systems (CPS), then we explore research directions for addressing these challenges.

1 Wireless automotive CPS: vision and challenges

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 CPSes, 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 [2]. Therefore, wireless networks such as wireless, embedded sensor networks have been envisioned to be a basic element of future automotive CPSes [5, 6]. 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 will be ubiquitously deployed and serve as a basic element of both intra-vehicle and inter-vehicle CPSes. In supporting mission-critical tasks, automotive CPSes pose stringent requirements on the predictability and reliability of wireless messaging. Nonetheless, wireless messaging is subject to the impacts of inherent uncertainties and dynamics within the system itself and from the environment in automotive CPSes.

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 behaviors. 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 [7, 9]. For instance, Figure 1 shows the network conditions in the presence of different traffic conditions, where network condition is represented by the unicast ETX (i.e., expected number of transmissions required to successfully deliver a unicast packet) for links associated with a randomly selected node in the Kansei testbed [3]. We see that unicast ETX changes significantly (e.g., up to 32.44) as traffic pattern and thus co-channel interference varies.

From the environment, a wide variety of factors can affect the behaviors of wireless messaging. Environmental factors such as temperature and humidity can affect wireless communication, electromechanical

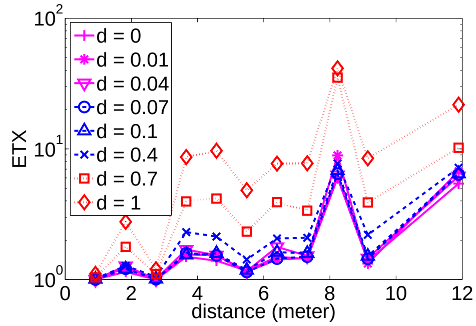

Figure 1: Link unicast ETX in the presence of different network traffic pattern. d denotes the probability that each node generates traffic at an arbitrary moment, and $d = 0$ denotes the case of no traffic in the network and thus zero co-channel interference. The data is for XSM motes (an enhanced version of MICA2 motes) and the B-MAC protocol, but similar phenomena are also observed when other MAC protocols (e.g., S-MAC) and radios (e.g., 802.15.4 and 802.11b radios) are used.

equipments in vehicles can introduce complex environmental noise, 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.

To enable predictable messaging and predictable behavior of wireless automotive CPSes, therefore, it is important to address the aforementioned systems and environmental dynamics. Given the potential resource constraints of wireless automotive CPSes (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 CPSes.

2 Elements of solutions

To enable predictable messaging for mission-critical wireless automotive CPSes, we need to take a holistic approach to addressing the impact of systems and environmental dynamics on the predictability and dependability of 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 systems and environmental dynamics in the design, analysis, and evaluation of automotive CPSes.

Since sensing, computing, messaging, and control are tightly coupled in automotive CPSes, 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 provide predictable 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 impacts on messaging behaviors. 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 [9, 8]; and we also need to design mechanisms for malicious attacks (e.g., jamming) to dependable 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 systems and environmental dynamics of wireless automotive CPSes, we should also try to take advantage of the unique properties of these CPSes. 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. To evaluate system design and modeling and analytical methods, we also need to develop experimental infrastructures that capture real-world dynamics and uncertainties in wireless automotive CPSes, and, to this end, we may need to collaborate with existing efforts and resources such as the NSF GENI (for *Global Environment for Network Innovations*) initiative [1].

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Author Biography. Hongwei Zhang received his Ph.D. in computer science and engineering from The Ohio State University in 2006, and he joined Wayne State University as an assistant professor thereafter. His research focuses on foundational and systems issues in designing dependable services for dynamic, large scale networked systems. His work explores new theories, methods, and systems building-blocks that address dynamics and uncertainties in providing predictable, dependable networking services for systems involving wireless networks, embedded networks, sensor networks, and the Internet.

Presently, he is especially interested in the modeling, algorithmic, and systems issues in wireless, embedded, and sensor networks. As a part of this effort and with support from the NSF GENI program, his research team are currently developing the theoretical and systems foundations for experimentation and service provisioning in federated, autonomous networked sensing. His work has also provided dependable services for several large scale wireless network systems including the NetEye experimental infrastructure (which has 130 IEEE 802.15.4 nodes and 15 802.11b/g nodes) and the DARPA sensornet project ExScal (which, with its 200-node 802.11b mesh network and 1,000-node mote network, is the world's largest wireless sensor network and likely the largest 802.11 mesh network deployed so far). More information about his work can be found from his website at http://www.cs.wayne.edu/∼hzhang/.