Asymptotically-Safe Formation Control in Vehicular Networks Communicating over Wireless Radio Channels

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Overview: Coordinated control of vehicular formations often occurs over a wireless radio network [16, 13, 12, 2]. The use of wireless networking injects a great deal of stochastic uncertainty into the formation control problem and such uncertainty clearly has a negative impact on system safety. This position paper examines a stochastic approach to the safety problem which requires that the likelihood of unsafe actions goes to zero as time goes to infinity. This is an *almost-sure* or *asymptotic* notion of stability [11]. Conditions under which asymptotic safety are enforced uses a switch controller architecture in which feedback information is dynamically quantized. These sufficient guarantees for asymptotic stability are established for a probabilistic model of channel burstiness that more accurately captures the state-dependence and burstiness in real-life vehicular radio links.

Prior Work: In a perfect world one would always want zero collisions, but this goal is unattainable. In the real-world, one must settle for bounding the likelihood of such collisions occurring. Traditionally, this has been done using mean-square (MS) concepts [9] in which the variance of some important system state, such as inter-vehicle distance, remains bounded. Systems that exhibit this property can be referred to as MS-safe systems. In reality, however, MS-safe systems are not that safe for at any point in time there is a fixed probability of a collision occurring. Rather than adopting a MS-safety criterion, we suggest using a stronger notion of *asymptotic* or *almost-sure* safety. With asymptotic safety the probability of a system state entering some forbidden or unsafe region of the state space asymptotically approaches zero as time increases. Asymptotic-safety, therefore, means that the system becomes more safe as time goes to infinity and in the limit one asymptotically approaches the ideal of ”zero collisions”.

One must be careful to specify the channel model under which asymptotic safety can be attained. Traditionally, this has been done using i.i.d. models of the channel. While such models may be appropriate for highly-coded stationary transmitters, the use of such models in vehicular communication is questionable since the channel state is often a function of the vehicle’s physical state [1, 3, 18]. This position paper makes use of a general probabilistic model of channel burstiness that is often called *exponentially bounded burstiness* (EBB) [19]. Such models are more general in the sense that they can characterize i.i.d. channels as well as bursty channels that are modeled as two-state Markov chains [17]. By using an EBB channel model that is functionally dependent on the vehicular states, this position paper is able to guarantee the asymptotic safety of vehicle formations in which the main source of uncertainty is the random variability in the communication channel’s state.

The asymptotically-safe controller presented in this position paper takes advantage of a priori knowledge relating channel burstiness to the system’s physical state [6]. The controller is a switched supervisory controller that dynamically quantizes feedback information to maximize the information flow across the time-varying channel. The switching decision is based on an estimate of the best performance that is achievable under current channel conditions and the current physical state. Under a suitable dwell time assumption this switching controller is able to guarantee asymptotic safety of the vehicle formation. These ideas have been applied to a chain of leader-follower pairs in which the upper (leader) vehicle determines the desired relative position of the lower (follower) vehicle [7]. The application uses a two-way communication link in which the leader transmits a desired ”relative position” to the follower and the follower sends back information on how well it can track the leader’s command. Under this controller architecture we have been able to demonstrate that the leader-follower chain is asymptotically safe.

Future Challenges: The prior work outlined above established a working framework under which asymptotic safety could be guaranteed in vehicular applications. The future challenge is to see whether some variation on this framework can achieve asymptotic safety for more general vehicular applications that have multi-user interference and humans-in-the-loop.

Multi-user interference occurs when multiple transmitters attempt to access the same channel at the same time. In large vehicular groups, one is bound to encounter significant levels of multi-user interference [14]. Such interference will be greatest when vehicles ”bunch” up together, and yet this is also the most important time when reliable inter-vehicle communication is needed to avoid collisions. In such an environment, maintaining almost-sure or asymptotic safety will be extremely challenging. Following insights from the prior work, the fact that interference levels are dependent on the group’s aggregate state suggests that one might again adopt a switching controller architecture that uses knowledge of channel state. A direct application of the prior work, however, will not be possible since interference is a property of the entire group of closely bunched vehicles. Since not all group vehicles are in direct communication with each other, we believe each vehicle needs to maintain a *situational awareness* of the entire group’s aggregated state. Following the framework outlined in the prior work, one could then adopt a switching controller architecture in which switching decisions are based on that estimate of the ”situational” state. One set of challenges therefore consists of how one might obtain estimates of the situational state in an environment with multi-user interference and how one would then design supervisory strategies for controller switching that can still assure some level of asymptotic safety.

The preceding paragraph suggested methods that ”switch” the control application’s structure in response to abrupt changes in the channel state, due to either fading or interference. In addition to adapting the physical controls of the vehicle to channel conditions, one may also consider coordinating the communication’s physical layer in response to changes in the group’s situational state. Such control of the communication layer has recently been enabled by the revolution in machine-to-machine (M2M) communication networks [4, 10]. M2M communication networks promise wireless networking with greater peak bit-rates and higher reliability than was previously possible. These technologies build upon the significant advances and economies of scale of the commercial wireless industry surrounding the 3GPP Long Term Evolution (LTE) mobile cellular and IEEE 802.11 wireless LAN family of standards [8, 15, 5]. Chipsets for both standards can achieve maximum data rates of 10-100 Mbps through the coordinated use of orthogonal frequency division multiplexing (OFDM) and adaptive modulation and coding schemes. It seems quite possible that M2M networking technologies will provide vehicles with an unprecedented level of control over their physical communication layer and that such control can be used in an effective way to actively manage the interference environment in a wireless network and thereby maintain a high level of connectivity for vehicles whose situational states are highly critical for safe collision-free operation.

Another important set of challenges revolve about how one might maintain asymptotic safety when there is a ”human” in the control loop. The prior work described a control architecture in which both supervisory decisions and direct vehicular controls are done by computer. We believe it is still possible to achieve safe operation when that vehicular control is done by a human operator. Future automobiles are expected to offer supervisory services to the driver, in which the computer warns the human operator of possible collisions and provides recommendations for avoiding such collisions. The recommendations made by the computer can be conditioned on the situational awareness of neighboring vehicles as well as estimates of how vigilant the human operators are in operating their vehicles. A future challenge for this project is to determine the extent to which asymptotic safety can be preserved in such a scenario.

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