1 RESEARCH OBJECTIVES

Page 1 Importance of Communications with Autonomous Vehicles

RI: I modified this based on PPT used on previous meeting

The research objectives of this project include studies of data source selection, of trajectory planning algorithms and performance limitations under communication latency and package error, and of packet receive by trajectory planning and control requirements. Table **??** provides a detailed list of technical objectives, along with the anticipated outcomes of pursuing them. In Section 9, we provide definitions of the terms related to "safety" mentioned in Table **??**. The scientific and engineering outcomes listed in Table **??** are expected to be strongly dependent – and the proposed work will characterize these dependencies – on the vehicle's forward speed, driving conditions (e.g. road topography and road surface), traffic conditions (e.g. average number of other vehicles per unit distance per lane, average speed of other vehicles), and driving maneuver (e.g. left/right turn, lane-keeping).

2 SUMMARY OF PROPOSED TECHNICAL APPROACH

page2 Proposed Research Contribution

RI: I modified this based on PPT used on previous meeting

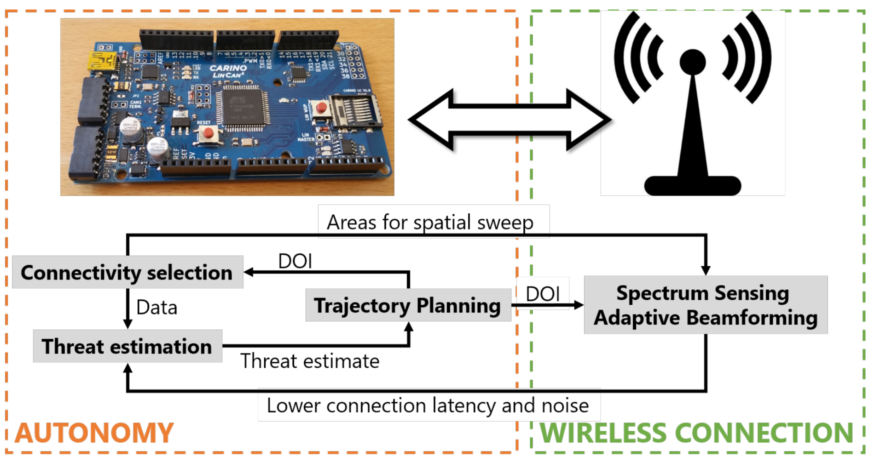

Figure 1: A block diagrammatic illustration of the proposed technical approach.

Scope of the project: We focus on how the wireless imperfections affect the control algorithm of lane keeping using BSM messages information from DSRC/WAVE standard in various scenarios. commands.

Terminology: We refer to the vehicle implementing the proposed algorithms as the *own vehicle*; to other possible connections, including other vehicles, smart infrastructure, and personal gadgets as *data nodes* or *nodes*; and to all collision threats, such as these nodes as well as static obstacles, as *other entities*.

The proposed technical approach consists of the following inter-related aspects (see Fig. 4):

1. **Transmission Imperfections**
2. **Heartbeat message BSM**
3. **Feedback Channels**
4. **Power control on emergency channel in DSRC**

   The DSRC define two emergency channel. The channel 172 is short range for accident avoidance and mitigation and channel 184 is long range and focus on road intersection collision mitigation. The proposal is to use two different power control strategy to maintain range of each emergency channel on a useful range to avoid interference.

5. **Robustness of control laws to imperfect communications:** All vehicles are represented by particle dynamical models. The control problem for the own vehicle is formulated as a problem of satisfying linear temporal logic (LTL) specifications under imperfect information. These specifications will encode the primary requirement of collision avoidance, as well as compliance with additional traffic regulations (e.g. maximum speed). The control problem for the own vehicle treats the data about positions and velocities of other vehicles as "sensor measurements." These data are inherently uncertain due to navigational uncertainty of each vehicle. Furthermore, these data are transmitted over imperfect communication channels that involve latency, dropped packets, and re-transmissions. The proposed work will characterize the robustness of control laws under such imperfect information, namely, the dependence of the probability of failure to satisfy the given LTL specifications on the nature of imperfections in data.

3 BACKGROUND AND PROBLEM IDENTIFICATION

Vehicular Ad-hoc Networks (VANET) is one type of Mobile Ad-hoc Networks (MANET) that specially designed for moving cars. Three types of VANET applications are provided:

Road safety applications including warning applications and emergency vehicle warning applications is the most valuable application of VANET. The safety application messages have the top priority among other communication services. The second type of application is Traffic management applications, which provides local and map information in order to improve traffic efficiency. The last type of application is for infotainment, which is based on the traditional IPv6 based internet.

VANET supports two types of communications: Vehicle to Vehicle (V2V) communication: in VANET, each vehicle will be equipped with an On Board Unit (OBU). V2V communication is between the OBUs of each vehicle mainly for road safety applications and traffic management applications.

Another type of VANET communication is Vehicle to Infrastructure (V2I). In VANET, the roadside infrastructure may be equipped with a RoadSide Unit (RSU). The V2I communication is between the RSU and the OBU mainly for infotainment applications.

VANET is based on several protocols. Basically saying, the physical and MAC layers are defined in IEEE 802.11p. The above layers are defined in IEEE 1609.x protocols, also known as Wireless Access in Vehicular Environment (WAVE) stack. The PHY layer is defined in IEEE 802.11p, which currently has been cooperated with IEEE 802.11-2012.

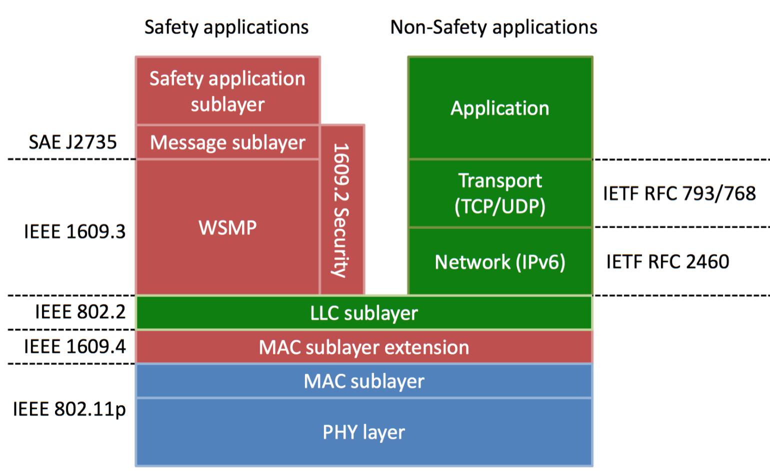

Figure 2: A block diagrammatic illustration of the proposed technical approach.

The physical layer of VANET is derived from IEEE 802.11a with 3 different channel width options: 5MHz, 10MHz and 20MHz, among which 10MHz is recommended. Same with 802.11a, 802.11p is using Orthogonal Frequency Division Multiplexing (OFDM) including 52 carriers, 48 data carriers and 4 pilots, and 8 us symbol interval. The physical channel supports BPSK, SPSK,16QAM and 64QAM.

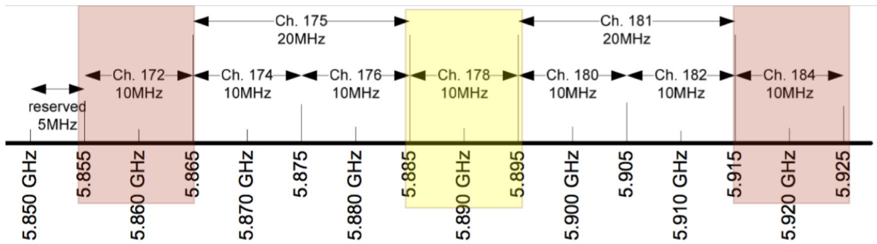

Figure 3: A block diagrammatic illustration of the proposed technical approach.

For the purpose of supporting safety applications, Dedicated Short Range Communication (DSRC) is developed. 75MHz spectrum in 5.9GHz frequency band is allocated for DSRC application, which includes 1 control channel (CCH) and 6 service channels (SCH). The CCH is for transmitting high-priority short control messages and management data. Among the SCHs, FCC defines Ch. 172 and Ch. 184 special for safety applications. SCH 172 is for V2V Safety communications for accident avoidance and mitigation, and safety of life and property applications. SCH 184 is for high-power, longer distance communications to be used for public safety applications involving safety of life and property, including road intersection collision mitigation.

In order to decrease the latency of communication under the high mobility environment, the MAC layer of VANET is also changed. Both IEEE 802.11p and IEEE 1609.4 define new characteristics of the MAC layer. In IEEE802.11, the wireless nodes could form a Service Set (SS), in which the nodes have the same Service ID (SSID) and share communication. The network with Access Point (AP) is called Basic Service Set (BSS) while a network with no AP, i.e., ad-hoc network, is named Independent BSS (IBSS). Several BSS could connect together to form Extended Service Set (ESS), all the BSS in one ESS is sharing the same Extended SSID (ESSID). The problem is forming a SS before the communication happened may take a lot of time, which is not suitable for fast changing VANET. Therefore, IEEE 802.11p proposed out of the context of BSS (OCB). The OCB mode applies to multiple devices within the coverage area of a single radio link. In the OCB mode, the vehicle can send or receive data any time without forming or being a member of an SS. In addition, IEEE 802.11p removed authentication, association and data confidentiality mechanisms from MAC layer and moved them to an independent higher layer defined in IEEE 1609.2. On the other side, IEEE 802.11p still keep the BSS mode, this is mainly for infotainment applications via V2I communication.

For medium access mechanism, traditional IEEE 802.11 is using Carrier Sense Multiple Access (CSMA)/Collision Avoidance (CA). IEEE 802.11p keeps CSMA, but not only that, it proposes Hybrid Coordination Function (HCF), which ensures Quality of Service (QoS) via Enhance Defense Cooperation Agreement (EDCA) defined in IEEE 802.11e. Data from different services has different priorities depend on the importance as shown in the table.

In addition to the IEEE 802.11p, IEEE 1609.4 defines multi-channel behaviors in MAC layer of VANET. As the PHY layer of VANET has 7 channels, IEEE 1609.4 depicts the channel switching mechanism among the CCH and SCHs.

IEEE 1609.3 defines two types of messages in VANET, Wave Short Message Protocol (WSMP) and IPv6 stack. IPv6 is usually for infotainment applications while the safety applications are transmitted via WAVE Short Messages (WSM).

SAE standards are made for the safety messages. SAE J2735 defines 15 types of safety messages such as Basic Safety Messages (BSM), Signal Phase Time (SPT) and MAP message. Specially, BSM is broadcast periodically in 10Hz announcing state information such as position, speed, acceleration and heading direction etc.

Message Priorities (SAE DSRC Message Framework Subcommittee DRAFT October 2008)
SAE DSRC Message Set & Priorities

Importance Level from USA FCC Policy	Description (When to apply a specific urgency level)	Description (When to apply a specific urgency level)
1 = Safety of Life Applies to those Messages and Message Sets associated with societal and/or safety impact related to human life.	Emergency Impact mitigation and injury avoidance/mitigation	Urgent warning of impending local situation
	Emergency Potential-event impact and/or injury mitigation and avoidance	Situation-based status information of uninvolved local interest
	Urgent Warning Events (Event Flags)	Intersection and vehicle safety status information
2 = Public Safety (Safety not in 1) Applies to Road Side Units (RSU) and On-Board Units (OBUs) operated by state or local governmental entities presumptively engaged in public safety priority communications. (Includes Mobility and Traffic Management Features)	Urgent public safety downloads (Intersection Information)	Semi-urgent public safety data and application enabler
	Public safety data transactions, exchanges	Important Traffic Management status information enabler
	Public safety geospatial context information	Important Announcement of WAVE Services
	Public safety RTCM GPS correction information	Non-urgent Traffic Management Foundational Data
	Semi-urgent public safety link establishment	
3 = Non-Priority Communications (Not in 1 or 2) Applies to Fleet Management, Traveler Information Services and Private Systems.	Urgent, private and commercial electronic transactions	Important, private and commercial electronic transactions
	Semi-Urgent, private mobility data and electronic transactions	Background, private mobility data downloads and upgrades

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Figure 4: A block diagrammatic illustration of the proposed technical approach.

In addition, SAE J2945 specifies the minimum communication performance requirements of the SAE J2735 DSRC message sets and associated data frames and data elements. In order to ensure interoperability between vehicles, SAE J2945 further defines BSMs sending rate, transmit power control, and adaptive message rate control etc.

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Two current trends promise to revolutionize the safety, reliability, and energy-efficiency of future automotive transportation [**?**]: (i) wireless connectivity of vehicles to each other (Vehicle-to-Vehicle, or V2V), to smart infrastructure (Vehicle-to-Infrastructure, or V2I), and to other mobile devices, and (ii) autonomy, ranging from driver assistance (L1 systems), to full self-driving autonomy (L4 systems). Connected autonomous vehicles (CAVs) are cyber-physical systems (CPS) with increasingly complex software algorithms in control of a physical vehicle moving in uncertain real-world environments.

The goal of this project is to investigate *bidirectional* interactions between the technologies of autonomy and of wireless connectivity in CPS. Using CAVs as a case study in CPS, we propose to investigate how estimation and control algorithms affect – and are affected by – software-defined radio communications in spectrum-scarce, data-rich environments. Copied from previous CPS proposal, should be changed

4 TRANSMISSION IMPERFECTIONS

The wireless communication channel may cause several transmission imperfections and those imperfections will affect the control algorithms in two ways.

The first problem is the communication delay, which contains processing delay, transmission delay and propagation delay. Processing delay is generated when the wireless node creates messages, encode or decode messages etc. Transmission delay is the time used to transmit one message, i.e., message length/number of transmitted bits per second. Propagation delay is decided by the distance and communication environment between the transceivers.

Communication delay varies a lot based on different hardware specifications of each communication nodes. And the delay may cause the control instructions arriving at the receiver disordered. For example, we want a vehicle to fully stop before making a right turn. Due to the communication delay, however, the vehicle receives the right-turn instruction ahead of stop instruction and then behaves in an absolute different way.

Another impact on the control algorithms due to transmission imperfections is the loss of control messages. Generally, the messages lost is caused by two reasons: packet lost and packet corruption. Packet lost is the situation when the receiver never receives the packet due to the multi-path effects or interference from other node. Packet corruption means the receiver has errors in decoding the received messages, those errors may be result from the collision with the other nodes or the noise of the wireless channel. The packet corruption can be detected in the decoding process via CRC check.

Packet lost also causes severe problems on the control algorithm. Suppose the vehicle should make a fully stop at the red signal light. If the stop control message is lost, the vehicle will keep moving and cause accidents. The emergency message already use the most robust MCS available so it need better power control to avoid lost of packages.

5 HEARTBEAT BSMS

SAE standards are made for the safety messages. SAE J2735 defines 15 types of safety messages such as Basic Safety Messages (BSM), Signal Phase Time (SPT) and MAP message.

Specially, BSM is broadcast periodically in 10Hz announcing state information such as position, speed, acceleration and heading direction etc. The BSM message is mandatory in DSRC that all vehicles need to broadcast to nearby cars.

In addition to the regular safety messages, BSM can be also used to transmit control messages. For the emergency channels, i.e., Ch. 172 and Ch. 184, BSM can convey power control information to coordinate the transmission power on each channel. On the other hand, the BSM can be used as the inputs of the vehicle control algorithms. The control messages are transmitted among the vehicles within the range.

The propose is to use this information to use as input for the power control algorithm and the control algorithms inside the car.

6 FEEDBACK CHANNELS

page6
feedback channels

7 POWER CONTROL

page7
power control with emergency channels

8 CONTROL ALGORITHM

page 8 Control Algorithm

9 TEST SCENARIOS

Subsections from previous CPS proposal, included here as a template, change for this proposal

9.a Connectivity Selection and Collision Threat Estimation

9.b Trajectory Planning: Method of Lifted Graphs

9.c Software-Defined Radio for Threat Reduction

9.d Experimental Validation

9.e Tools

9.e.1 Simulation of Urban Mobility (SUMO)

The SUMO [1] is a traffic simulation available since 2001. It uses single vehicles models driving in a given road from a defined route. Each car is defined by a unique identifier, the depart time and route. Car-following models are use to define the current speed of vehicle based on distance and speed of the lead vehicle. [2]. This behavior of the cars can be change using external algorithms and TRACI in 9.e.2 shows how. The simulation is a time-discrete simulation. The defaults step is 1s but it can lower to 1ms.

The roads defined in the scenario files are represented in simulation as graphs. The intersections are node and the road are edges. This road networks can be generated manually or imported from a digital road map like VISUM [3] or OpenStreetMap [4]. The available digital road networks are deigns for navigation. So they lack the detail need for traffic simulations like traffic lights and lane information, so the SUMO tools use heuristics that have more details in [5] .

Another important aspect is the definition of routes inside the simulations. SUMO needs the complete list of connect edges , start and end time of the vehicle. However Traci can use an external control algorithm to modify the route.

9.e.2 Traci

In 2006, the SUMO was extend to make interactive simulation using socket connection. The API called TraCI for ”Traffic Control Interface”. [6] The behavior is client and server structure. The SUMO start listen to a defined port for incoming connections. When a client connect, it is responsible for the main simulation loop and it have access of almost all simulations artifacts.

The client implementation can be coded in Python, Java or any language that support a tcp socket. The main focus will be the traci for matlab. [7].

10 ADMIN STUFF

page 13-15
Admin Stuff

10.a Results of Prior NSF Support

Need to add VTS travel award, and MRI

The PI’s prior NSF support in the last 5 years:

1. **Title:** EARS: Adaptive Behavioral Responses for Dynamic Spectrum Access-Based Connected Vehicle Networks. **Total Award Amount:** $299,840.00 **Total Award Period Covered:** 01/01/16 - 12/31/18. **Investigators:** PI: Alexander M. Wyglinski, Co-PI: Robert Gegear, Co-PI: Elizabeth Ryder. Currently project studies how dynamic spectrum access (DSA)-based vehicular networks can be combined with foraging theory concepts employed by bumblebees. Resulting publication: [6]. NSF award number 1547291.

2. **Title:** WiFiUS: Collaborative Research: Future Small-Cell Networks Using Reconfigurable Antennas. **Total Award Amount:** $90,161 **Total Award Period Covered:** 02/01/15 - 01/31/17. Investigators: PI: A. M. Wyglinski. Currently developing practical reconfigurable antennas and transceiver processing techniques for small-cell base stations. Resulting publications: [1-5]. NSF award number 1457310.

3. **Title:** STTR Phase II: Reconfigurable Wireless Platforms for Spectrally Agile Coexistence. **Total Award Amount:** $748,847 **Total Award Period Covered:** 04/15/14 - 09/31/16. **Investigators:** PI: Samuel MacMullen, Co-PI: A. M. Wyglinski. Currently developing digital predistortion strategies for

spectrally agile transceivers using non-contiguous portions of spectrum in parallel for high-speed data transmission. Resulting publications: [7] NSF award number 1353600.

4. **Title:** STTR Phase I: Reconfigurable Wireless Platforms for Spectrally Agile Coexistence. **Total Award Amount:** $150,000 **Total Award Period Covered:** 07/01/12 - 06/31/13. **Investigators:** PI: Samuel MacMullen, Co-PI: A. M. Wyglinski. Developed a functional prototype of a spectrally agile transceiver that would be able to use non-contiguous portions of spectrum in parallel for high-speed data transmission. Resulting publications: [118]. NSF award number 1212340.

References

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[3] P. Group, "Ptv visum @ONLINE." http://vision-traffic.ptvgroup.com/en-uk/products/ptv-visum/, Oct. 2016.

[4] OSMF, "Openstreetmap." http://www.openstreetmap.org/, Oct. 2016.

[5] D. Krajzewicz, G. Hertkorn, J. Ringel, and P. Wagner, "Preparation of digital maps for traffic simulation; part 1: Approach and algorithms," in *Proceedings of the 3rd Industrial Simulation Conference 2005*, pp. 285–290, EUROSIS-ETI, 2005.

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[7] A. Acosta, "Traci4matlab." http://www.mathworks.com/matlabcentral/fileexchange/44805-traci4matlab, Oct. 2016.