MOVESET: MOdular VEhicle SEnsor Technology

Qi Chen, Brendan Bellows, Mike P. Wittie
Gianforte School of Computing
Montana State University
Bozeman, MT 59717
moveset@sympa.montana.edu.

Stacy Patterson
Department of Computer Science
Rensselaer Polytechnic Institute
Troy, NY
sep@cs.rpi.edu

Qing Yang
Gianforte School of Computing
Montana State University
Bozeman, MT 59717
qing.yang@montana.edu

***Abstract*—New vehicles are being equipped with a variety of on-board sensors, as well as DSRC and cellular radios. These sensors and connectivity capabilities create opportunities for innovative applications for flow control, route planning, and road safety. Such applications rely on up-to-date data transmitted by the vehicles to analyze real time road and driving conditions. Due to the time-sensitive nature of these data, it is important to identify and understand connectivity characteristics that impact vehicle data sharing and communication, including both vehicle-to-vehicle communication through DSRC and vehicle-to-infrastructure communication through cellular channels. We present MOdular VEhicle SEnsor Technology (MOVESET) – a low cost vehicle sensor package that allows independent research groups to create datasets of vehicle sensors readings correlated with measurements of cellular and DSRC connectivity. We also present a dataset of measurements conducted in September of 2016 on an interstate and rural highways along the Bozeman, MT, Billings, MT, Red Lodge, MT, Bozeman, MT route. We hope that the MOVESET sensor platform and the presented dataset will make it easier for the research community to design and evaluate data integration applications for connected vehicles.**

I. Introduction

New connected vehicle standards offer unprecedented potential for vehicle information sharing and cooperation. Vehicles are already equipped with a variety of on-board sensors, as well as cellular and Dedicated Short Range Communications (DSRC) radios [1], [2]. These sensors and connectivity capabilities create opportunities for innovative applications for flow control, route planning, and road safety, among others. Such applications rely on up-to-date data transmitted by the vehicles to analyze real time road and driving conditions.

Due to the time-sensitive nature of these data, it is important to identify and understand connectivity characteristics that impact vehicle data sharing and communication, including both vehicle-to-vehicle communication through DSRC and vehicle-to-infrastructure communication through cellular channels. Further, as the number of participating vehicles grows, the increasing communication traffic of these applications will drive network congestion and, in the case of cellular networks, costs, making vehicle-to-vehicle (V2V) communication an increasingly important for application performance. Thus, to develop robust, scalable, and performant vehicular applications, the research community needs accurate datasets that include sensor data as well as V2V and vehicle-to-infrastructure (V2I) connectivity.

We present MOdular VEhicle SEnsor Technology (MOVESET) – a low cost vehicle sensor package that allows independent research groups to create datasets of vehicle sensors readings correlated with measurements of cellular and DSRC connectivity. MOVESET has the potential to increase the geographic coverage of connected vehicle data into areas not included in current connected vehicle trials [3], [4], [5], notably on rural roads and off-road areas. We describe the low cost design of our sensor platform (under $170) and make available all the hardware specification, configuration files, measurement scripts, database schema, and 3D print models to allow other groups to replicate MOVESET nodes [6]. MOVESET is modular and can be expanded with additional sensors and network interfaces (radios) to suit a wide range of deployment scenarios.

We also present a dataset of measurements conducted in September of 2016 on an interstate and rural highways along the Bozeman, MT, Billings, MT, Red Lodge, MT, Bozeman, MT route. In additiona to sensor readings, MOVESET measurements show comparative performance of cellular and DSRC communications in rural areas – data that is currently not represented in the FHWA Research Data Exchange (RDE) [7]. Our measurement show the impact of rural and mountain topography on DSRC and cellular connectivity with implications for distributed application design and future V2X cellular standards.

We hope that the MOVESET sensor platform and the presented dataset will make it easier for the research community to design and evaluate data integration applications for connected vehicles. In the near future we will expand the availability of MOVESET data with measurements in several additional locations including Wyoming and New York. We will also make available Veins simulation scenarios, configured to reflect MOVESET sensor and network measurements, to allow repeatable algorithm experiments.

The rest of this paper is organized as follows. Section II presents the related work on vehicular sensing applications, testbeds, and datasets, as well as a short overview of challenges in distributed sensing. In Section III we described the architecture of MOVESET. Section IV details our data collection process and the dataset we make available. Finally, we conclude and offer directions for future work in Section V.

II. Related Work

To illustrate the importance and challenges of obtaining a correlated data set of vehicle sensor readings and connectivity, we present related work on vehicular sensing applications, existing testbeds, and commercially available sensor hardware.

A. Vehicle Sensor Networks

In the past several years, a flurry of applications have been developed that integerate time-sensitive sensor data from multiple vehicles. Several of these, the CarTel system [8] and the Pothole Patrol [9], use a paradigm where all sensor data is routed opportunistically to a fusion center using WiFi or cellular. In the Mobeyes project [10], vehicles collect sensor data and independently summarize it. These summaries are then diffused through the network using V2V communication so they can be harvested by special probe vehicles. The CARLOG project [11] proposes a Datalog-like framework for event-driven applications such as notifying a driver when he or she is driving too quickly. The framework combines data from on-board sensors with global information source such as weather to determine when to make notifications. These applications demonstrate the potential benefit of integrating data from mutiple vehicles to support safer driving conditions. The sensor and connectivity datasets provided by the MOVESET project will support development new vehicular network applications in this vein. These datasets will allow researchers to more easily evaluate application performance for various architectures and scenarios.

B. Connected Vehicle Testbeds

Recent years have seen the expansion of vehicular testbeds [3], [4], [5] and testing grounds [12], [13], [14], [15]. While this work has greatly increased the availability of data on connected vehicles, the variety of vehicle connectivity and network performance data necessary to develop vehicular sensing applications remains limited. The Connected Vehicle Pilot Deployment Program performs connected vehicle trials in New York, NY, Tampa, FL, and along the I-80 in Wyoming [3]. Measurements of vehicle connectivity are restricted to DSRC links; vehicle cellular connectivity is not considered and only the Tampa test site includes pedestrians with a mobile application. The Connected Vehicle Test Bed includes sites in Michigan, New York, Florida, Tennessee, and Virginia [4]. While the vehicles in some of these sites include cellular connectivity, the data available from these sites do not include cellular measurements [7].

Other testbeds have focused on experimentation with small autonomous vehicles [16], [17], [18], [19], [20]. These solutions, however, support experimentation in relatively controlled indoor environments, as opposed to data collection on public roads or in other outdoor scenarios. Systems by Labrado *et al.* and Cruz *et al.* supports cloud control of autonomous vehicle swarms[16], [20]. Their system connects vehicles through a WiFi router, which does not realistically model vehicle-cloud network performance. Jiang *et al.* also connect nodes via WiFi, but the connectivity between physical nodes follows performance of NS-3 simulations configured to model outdoor scenarios [17]. Unlike our work, the simulations are not based on measurements and are limited to the small number of vehicles in the physical testbed.

C. Vehicular Sensors and Data Acquisition

Although vehicles are increasingly equipped with a variety of sensors, the acquisition of their data remains difficult. Vehicle sensors are connected to the Controller Area Network (CAN bus), which can be accessed through the On-board Diagnostics (OBD-II) interface. While OBD-II is theoretically a standard, many manufacturers do not necessarily respect the standardized PIDs (Parameter IDs) [21]. Many of the OBD-II PIDs and CAN bus message IDs are considered sensitive by the manufacturers and are not available to the general public. Ford engineers have developed an abstracted protocol known as OpenXC that manufacturers can use to implement a read only API for a select set of defined CAN messages [22]. At this time however, Ford is the only manufacturer to provide OpenXC compliant software for their vehicles [23]. Reverse engineered databases of CAN messages exist and can be used to decipher common data from the CAN bus, but these often need to be updated with each new model year from each of the manufacturers as no industry standard exists [24].

In addition to the physical difficulty of reverse engineering and then maintaining a reliable database of CAN messages, a major legal barrier is in place. The EPA (which mandates the presence of OBD-II and OBD-II over CAN) has declared tampering with any part of a certified vehicle emissions system to be a federal offense. The OBD-II and CAN components comprise a portion of the emissions system, and as a result, any modification to the certified and compliant communications system may be considered a violation of EPA regulations [25]. Therefore, innovation in vehicle sensing to increase the availability of vehicle research data must rely on add-on sensors.

While there are many commercially available vehicular sensors, which can be interfaced with a laptop for data collection, the cost of instrumenting a vehicle using that route is quite high. For example, a road temperature and humidity sensor with a USB interface costs around $160 [26], while the probes themselves are only around $40 [27], [28]. Although a data acquisition module (DAQ) can integrate inexpensive analog (temperature, humidity) and digital (GPS, accelerometer) sensors, its cost may run into many hundreds of dollars [29], [30] At the same time an Arduino board used in MOVESET for the same function is only $45 [31]. Thus to lower the cost of vehicular data collection, we opted to develop the MOVESET sensor package based on an Arduino board and compatible sensors and make the design publicly available for other research groups.

III. MOVESET

The MOVESET sensor package, shown in Figure 1 combines several sensors. We collect GPS location, 3-axis accelerometer, gyroscope, and magnetic reading, and temperature and relative humidity. To ensure accurate readings the

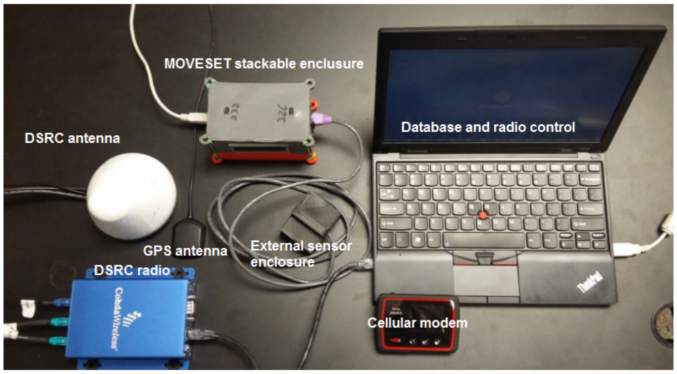

Fig. 1. MOVESET node and radios.

GPS sensor uses an external antenna, while the temperature and humidity sensors are mounted under the vehicle in an external enclosure connected via the I2C bus over Ethernet. The cost of the parts and materials for MOVESET, not including the radios, is under $170.

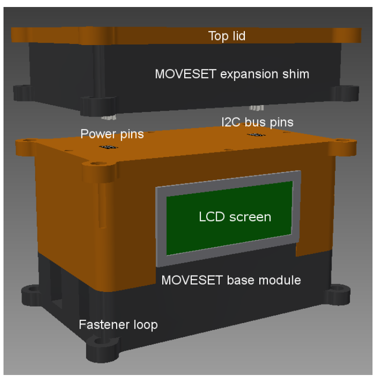

Fig. 2. MOVESET expansion through shims.

A key innovation of MOVESET is its extendability. Sensors may be added to the base platform through *shims* stacked on top of the base module, as shown in Figure 2. The ports on top of the base enclosure pass power and I2C bus pins to the shims on top. External fastener loops hold the shims together with rubber bands for easy disassembly, or threaded rods for more permanent binding. To support extension of MOVESET with arbitrary sensor combinations, the main module performs sensor autodiscovery and displays the status of available sensors on its LCD.

We have also interfaced MOVESET with DSRC and cellular radios. We have used the Cohda Wireless MK5 On-Board-Unit (OBU) to measure V2V connectivity and two cellular modems from AT&T and Verizon wireless to measure the performance of V2X connections. We measured network latency and packet loss with `ping` and available bandwidth using `iperf` (15 s measurements). While the cellular modems provide only one channel, we were able to perform a series of network measurements between the DSRC radios using different channels and modulation rates. The network measurement scripts are currently executed on a laptop, but a future version of MOVESET will replace the laptop with an Arduino board MOVESET shim.

We are making the design of MOVESET available through the project website [6]. The site contains all the hardware elements, configuration files, scripts, and 3D print files for the enclosures. We hope that these data will make it easier for other research groups to create their own versions of MOVESET units and expand them with additional sensors suitable to their measurement scenarios.

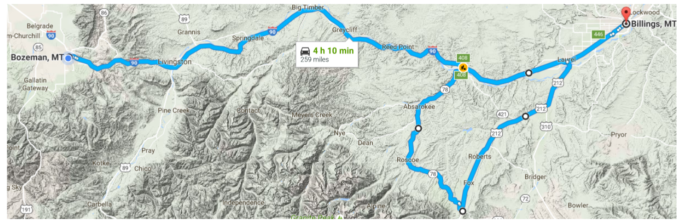

Fig. 3. Measurement route.

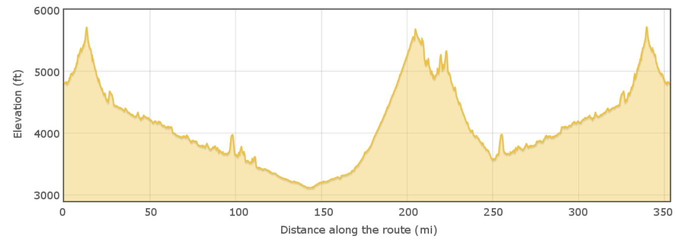

Fig. 4. Measurement route elevation.

IV. Dataset

To capture sensor and network connectivity data in rural conditions, we performed a measurement drive along a loop between Bozeman, MT, Billings, MT, and Red Lodge, MT shown in Figure 3. This route includes several elevation features representative of the Mountain West Region, including a mountain pass (Bozeman Pass), relatively flat prairie (between Big Timber and Laurel), and remote mountain roads (along MT-78 and US-212). We illustrate the elevation change along this route in Figure 4. We collected data from two vehicles traveling at an average of 121 m apart on I-90 and 61 m apart on MT-78 and US-212. The first vehicle carried the MOVESET sensors, cellular modems (AT&T and Verizon), and a DSRC OBU. The second vehicle carried the second OBU for measurement of DSRC connectivity between the vehicles. We present the summary of the network performance data in Table I. Detailed network and sensor data are available on the project website [6].

Network	Latency (ms)			Throughput (Mbps)		
	Min	Mean	Max	Min	Mean	Max
DSRC (BPSK)	1.36	318	826	2.31	2.48	2.67
AT&T	150	726	6500	0.4	1.55	3.49
Verizon	80.9	479	9194	0.23	1.66	4.42

TABLE I
MEASURED NETWORK PERFORMANCE.

Overall, we have observed that the topographical conditions of our route resulted in different connectivity profiles for DSRC and cellular communications. Flat open spaces favor good radio wave propagation, and predictably, DSRC connectivity remained strong, even as the test vehicles became separated by other cars on the road. Although DSRC latency remained stable, greater distance between vehicles, up to 411 m, resulted in slight lowering of throughput. The cellular latency and throughput suffered under poor signal strength to distant towers. Cellular connectivity remained performant in well populated areas but became spotty along mountain roads connecting remote communities around Red Lodge. Overall, AT&T provided coverage for 75.5% of the route and Verizon for 96%. Finally, we have observed that cellular connectivity provided much higher latency and generally lower bandwidth than DSRC.

Our observations of the differences between DSRC and cellular network performance motivate future work on creating a V2V communication model that use both channels. Although the higher delay and generally lower bandwidth of current LTE networks is not considered suitable for safety applications [32], the greater range of cellular networks with respect to DSRC, may make them preferable for vehicle flow coordination and distributed sensing applications. In our future work, we plan to show how to implement such applications by leveraging DSRC and cellular channels in unison. We hope that this future direction and additional planned measurements in urban areas will also shed light for the design of 5G-based Device-to-Device (D2D) standards in the 3GPP V2x group [32].

V. Conclusions and Future Work

MOVESET introduces an inexpensive, open-source sensor platform for connected vehicle experimentation. MOVESET is modular and can be expanded to measurements in a variety of scenarios, including off-road and smart agriculture settings. Our first dataset, collected in rural Montana, integrates several vehicle sensors with measurements of DSRC and cellular network performance. We make these data publicly available through RDE [7] and the project website [6].

Our future work will focus on additional measurement rural and urban scenarios, including the Wyoming and New York. Unlike Montana, these sites support measurements of DSRC V2I connectivity through road side units (RSUs) deployed as part of the Connected Vehicle Pilot Deployment Program [3]. Our goal is to create Veins [33], [34] simulation scenarios, where distributed applications for distributed sensing and vehicle flow control may be evaluated at a lower cost. We also plan on expanding MOVESET with additional sensors, such as infrared road surface condition sensors.

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