Network driven performance analysis in connected vehicular networks

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Abstract—As the adoption rate of connected vehicle technology and the complexity of associated vehicular applications grows, the load on the supporting connected vehicular network will also grow accordingly. Sustaining future application requirements will necessitate network optimization. To that end, a comprehensive understanding of network behavior under different operational conditions is essential. This paper studies vehicular network performance in a DSRC/IP network in terms of a set of network indicator metrics that are controllable through adjustments to lower layer parameters within the DSRC stack. We present and analyze results using DSRC enabled hardware modules that are substantiated and validated through our integrated simulator.

I. INTRODUCTION

Advancements in vehicular technology are rapidly reshaping the human driving experience with recent manifestations including connected and autonomous vehicles (CAVs). Predictions show that 25% of all vehicles in U.S. will be fully autonomous by 2035, and 100% will be fully autonomous by 2050 [1]. Once widely deployed, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) technology will lead to more efficient use of the nation's traffic infrastructure and to reduced energy usage. As the penetration level of autonomous vehicles grows, there will be fewer vehicular accidents and fatalities. We refer to vehicular communications either to other vehicles or to infrastructure as Vehicle-to-Everything (V2X). Today's V2X applications provide a range of safety, mobility, and environmentally oriented vehicular applications. As market demand for vehicular entertainment features increases, a new class of data intensive content sharing and consuming applications that can be used for user-oriented event sensing and processing, locality-aware personalized suggestions, and multimedia streaming is brought forth [2]. As society adopts autonomous vehicles, new application systems that support CAVs will need to be developed. As these systems involve the safety of humans, the underlying distributed network and compute systems will require fine-grained control of system resources. To optimize vehicular network resources and performance in the face of this impending development, a comprehensive understanding of the vehicular network behavior and factors impacting network performance is essential.

In this work, we aim to provide an understanding of vehicular network behavior subject to modification of various parameters within the lower layers of the Dedicated Short Range Communications (DSRC) stack. We define network performance as a function of *indicator metrics* consisting of throughput, latency, channel busy ratio (CBR), and packet delivery ratio (PDR). We further posit that lower layer parameters within the DSRC stack including the modulation and coding of frame transmissions, choice of access category, and transmit power can cause performance variation reflected by the indicator metrics. We investigate this performance variation through experimental results obtained with hardware testing using DSRC enabled modules in the lab and South Carolina Connected Vehicle Testbed (SC-CVT) [3], and validate and extend the same with simulation testing. Simulation testing is conducted via non-mobile and mobile simulation models. The non-mobile simulation model compares directly to the hardware tests and uses the discrete event network simulator ns-3 [4]. The mobile simulation model uses an integrated simulator that utilizes realistic semi-urban traffic network of the SC-SVT testbed to substantiate and extend hardware test results.

The rest of the paper is organized as follows. Section II provides an understanding of DSRC protocol and the network performance indicator metrics within the context of this work. Section III details the hardware and simulation test setups, and describes the conducted tests. We present the results obtained from testing and analyze them in Section IV. Section V concludes this paper with a proposed plan to extend this work in future.

II. BACKGROUND

Vehicular networks can involve any current standards-based wireless technology and will involve emerging technologies that are currently under development or that have yet to be invented. The simplified network paradigm in this work considers DSRC equipped on-board units (OBUs) in vehicles broadcasting information rich messages in a V2X context. A vehicle equipped with an OBU is referred to as a node within the context of this work. DSRC uses 802.11p Wireless Access for Vehicular Environments (WAVE) at the physical (PHY) and Media Access Control (MAC) layers; and IEEE 1609.x or IPv6 at the network layer. At the network layer, 1609.3 (networking services), 1609.4 (channel switching), and 1609.2 (Security services) are used. 1609.3 includes the WAVE Short Message Protocol (WSMP). Applications can chose between using WSMP, or IPv6 with TCP/UDP depending on their requirements. DSRC operates on a dedicated spectrum of

75 MHz in the 5.9 GHz band through seven channels with bandwidth of 10 MHz each. While there is provision to pair consecutive channels to form a 20 MHz channel, 10 MHz channel width is found to work better in the vehicular context [5]. One channel in the DSRC spectrum is designated as a control channel (CCH) while all other channels are service channels (SCHs).The WAVE 1609.3 and 1609.4 standards define various classes of channel assignment based on the capability of the device to behave as a single-PHY or multi-PHY device. A single-PHY device can support a single radio while a multi-PHY device can support dual radios. Various channel utilization models are supported [6]. For this study, we consider single channel operation using only one CCH or SCH.

At the PHY layer, 802.11p uses orthogonal frequency division multiplexing (OFDM) protocols with four modulation techniques, BPSK, QPSK, 16-QAM, and 64-QAM.These modulation techniques are supported through 8 combinations of modulation rate and forward error correction coding rate resulting in support for data rates of 3 Mbps to 27 Mbps [5]. Higher data rates correspond to reduced channel loads in environments with higher aggregated communication load. QPSK with rate 1/2 coding, equivalent to a data rate of 6 Mbps, is considered the default in the U.S. since it provides a good trade off between signal-to-noise ratio requirements and the channel load [5]. At the MAC layer, 802.11p follows the medium access method, carrier sense multiple access/collision avoidance, as specified in IEEE 802.11. Quality-of-service (QoS) is provided through Enhanced Distributed Channel Access (EDCA) where different priority levels are implemented using different back-off and idle time [7]. 8 user priority levels mapping to 4 access categories (AC) are supported. The 4 ACs are defined as *voice* (AC3), *video* (AC2), *best-effort* (AC1), and *background* (AC0), and map to 2 user priorities per category. The ordering of ACs from lowest to highest priority is AC0, AC1, AC2, and AC3 [8]. Frames to be transmitted are placed in the queue corresponding to the specified priority level, and priority is implemented via varying inter-frame spacing and contention window size translating to shorter queue delays for higher priority queues. The minimum values of contention window (CW_{min}) for AC0, AC1, AC2, and AC3 are 15, 15, 7, and 3, respectively. We refer to the different priority queues corresponding to AC0, AC1, AC2, and AC3 as background, best-effort, video, and voice priority queues.

A. Network Indicator Metrics

We adopt the following metrics to evaluate network performance.

a) Throughput: Network throughput is defined as the rate at which a node receives incoming packets. Network conditions like signal to noise ratio, number of contending devices, channel width etc. can impact network throughput. To study the bounds of network performance, the effective throughput available to support vehicular applications is important. Effective throughput is theoretically calculated for choice of modulation scheme, application protocol data unit, priority queue, and arbitration delay factors. We use calculations in [9] as references for our work.

b) Latency: End-to-end application layer latency is a factor of queuing delay, propagation delay, channel access, and contention. For L latency measurements, $L = l_0, l_1, l_2, ..., l_n$ over n successful receptions in a time window T, average end to end latency is defined as,

$$\tau = \sum_{n=1}^{n} \frac{L_n}{n}$$

c) Channel Busy Ratio (CBR): The amount of time a node finds the channel occupied while conducting arbitration for transmission is referred to as the channel busy ratio. In Cohda MK5 modules used for this study, a channel is considered busy when received power is above a specified threshold value (-85 dBm) [10]. CBR is measured as the percentage the channel is found busy over a measurement time period . It should be noted that within a large scale wireless system, CBR is a subjective value observed differently at nodes depending on their vantage point within the system. Hence, choice of CBR measurement node in such systems must be made strategically.

d) Packet Delivery Ratio (PDR): PDR, a measure of network reliability, is defined as the ratio of the number of actually received packets to the number of expected received packets for a given communication range.

III. METHODOLOGY

We identify message size, modulation and coding scheme (MCS), priority queue setting, and transmit power as a set of *control metrics* whose modification would influence *network indicator metrics* defined in section II. The tests in this section are devised to investigate the consequences of modifying control metrics. Conducted tests can be categorized as hardware and simulation based tests. The hardware tests are used to characterize network performance impact in a real world scenario. Performance from hardware tests is compared to simulation tests. Simulation tests are further used to extend observed results by testing behavioral variation under realistic network load conditions.

A. Hardware tests

Cohda Wireless' MK5 modules [10] are used for the hardware tests. MK5 OBUs are equipped with dual 802.11p radios supporting DSRC communication and connected to an embedded Linux system using a high speed USB bus. Two antennas are employed with the possibility of using either or both antennas for a given radio channel. The OBUs can be configured to use user-defined channel(s), radio(s), antenna(s), and MCS rate. A MAC/Logical Link Control (LLC) processor allows periodic monitoring of various specifics during transmission, including MCS rate, priority queue, size of data being transmitted and received, and transmit power being used. Conducted hardware tests were done with OBUs configured to use single-radio, single-channel communication with both antennas, varying MCS rate, transmit power, and priority queue values. A constant bit rate measurement application was developed for this study. This application allows broadcast transmission using User Datagram Protocol (UDP) over the

DSRC/IP network with user-defined message size, transmission rate, number of messages to be transmitted, and the priority queue to be used. At the receiving node, the application measures per-packet one-way latency values, overall throughput of transmission, and total bytes of data received from incoming messages. MCS rate at the transmitting node and the CBR at the receiving node can be set and measured respectively using the Cohda provided LLC utilities.

Hardware tests were conducted in the lab environment and in the SC-CVT testbed at Clemson University. The objective of the lab tests was to observe the impact of modifying control metrics without considering channel noise. These tests were conducted with 2 OBUs placed within close proximity and in line of sight. Fig. 1a shows the lab setup used for testing. Control metrics were modified in the manner described above within the transmitting OBU and the impact was measured on the receiving OBU. Lab tests were conduced where throughput, latency, and CBR were measured for different MCS and message sizes. To examine the impact of priority queue settings, two instances of the measurement application were run on each OBU with the first application instance using the *best effort* priority queue for transmission and second application instance using varying priority queue settings. Both applications were additionally using the same transmission rate. The objective of the test was to study how the packets queued in varying priority queues from the second application instance impacted the performance of the packets queued in the *best effort* queue from the first application instance.

In addition, tests in the SC-CVT testbed were conducted where the Tx-Rx communication range between the OBUs was incrementally increased from 0-100 meters. Two OBUs were installed on two vehicles and the latency was observed for a fixed MCS (R12QPSK), and variable message sizes and Tx-Rx communication ranges. These tests were compared to simulation results with the objective of establishing comparability between the hardware and simulation test results. Fig. 1b shows one of the vehicles used in this test. Calculation of performance indicator metrics, especially latency, is conditional on precise time synchronization between nodes. Implementation of Network Time Protocol (NTP) in our testbeds was done with chrony [11]. Chrony was selected on account of its ability to provide precise time synchronization in networks susceptible to conditions like intermittent connectivity and congestion. All presented hardware tests were done using DSRC/IP/UDP with broadcast transmissions, but initial testing of throughput and latency with DSRC/WAVE showed comparable results to DSRC/IP. Hence,the applicability of obtained results to either environment can be extrapolated.

B. Simulation tests

Simulation tests were done to provide an understanding of how the impact of control metrics propagates with increasing network load. A supporting objective of simulation testing was to assess the comparability of performance in the simulation environment and the hardware environment. Two types of simulation testing were done using mobile and non-mobile simulation models. The non-mobile simulation model was used for direct comparison to the hardware tests results as

(a) Lab setup.

(b) Clemson University testbed setup.
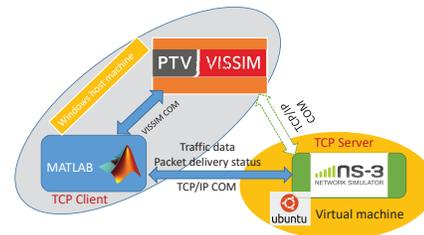
Fig. 1. Experimental setup for hardware testing.

Fig. 2. Integrated simulator for mobile simulation testing.

those were done in a non-mobile environment as well. DSRC PHY and MAC layers standards were used for the simulations.

a) Non-mobile simulation model: The non-mobile simulation model was developed in ns-3. A scenario with incrementally increasing Tx-Rx communication range between 2 vehicles was simulated in ns-3 to compare with results observed using hardware testing. Further, to examine bounds of network performance in a network 'under stress', a test was conducted to observe the impact on latency as channel utilization approached 100%. 100% channel utilization was simulated by all nodes transmitting at maximum achievable throughput. The channel model used in the simulation considered an urban scenario with log distance path loss model and Nakagami-m fast fading loss model [12].

b) Mobile simulation model: An integrated simulation model was developed for jointly simulating the network and vehicular traffic. Fig. 2 shows the integrated simulator, which consists of PTV VISSIM for traffic simulation [13], ns-3 for discrete-event network simulation, and MATLAB scripting for setting up traffic parameters in VISSIM through VISSIM COM (Component Object Model). Real-time communication between ns-3 and VISSIM was set up via TCP/IP socket Application Programming Interface. Using VISSIM simulator, roughly 1 mile long two-lane bi-directional traffic in the neighborhood of SC-CVT test bed was simulated.

The VISSIM COM interface, through MATLAB scripting,

Fig. 3. A portion of vehicular traffic simulation with PTV VISSIM at the SC-CVT testbed in Clemson University.

TABLE I
VISSIM AND NS-3 SIMULATION PARAMETERS

Parameter	Value	Default
Number of vehicles	2∼100	60
Safety message size	184∼1350 bytes	368 bytes
Transmission rate	10 Hz	
Carrier frequency	5.9 GHz	
Channel bandwidth	10 MHz	
Channel access	802.11p OCB	
Data rate	3∼27 Mbps	6 Mbps
Transmit power	7∼30 dBm	30 dBm
Communication range	100∼1000 m	300 m
VISSIM update rate	0.1 sec	
Simulation time	50 sec	

was used to initiate the desired test track network in VISSIM and send and receive traffic parameters/data in VISSIM-MATLAB interface. In every simulation step (at 100 msec interval), MATLAB sent VISSIM vehicles' position information to ns-3, and ns-3 used the waypoint-mobility-model to create and track the vehicle's position and speed. Messages were sent at a rate of 10 Hz (10 packets/second) using the parameter settings shown in Table I.Fig. 3 shows a portion of VISSIM test network. The justification for parameters' values used in Table I can be found in [5], [14]–[16]. Other than these explicitly listed parameters, simulation was conducted under the simulator's default settings.

IV. RESULTS AND ANALYSIS

In this section, we present and analyze the experimental results from the tests conducted in section III.

### A. Experimental results from hardware tests

a) Impact of different MCS rates and message sizes: Fig. 4a shows the throughput, CBR percentage, and latency for each MCS rate at varying packet sizes. In [9], the authors found that sending UDP broadcast traffic at rates approaching the effective throughput values results in queuing losses. The throughput shown in Fig. 4a is the maximum throughput achievable without incurring any queuing losses. The transmission rate for this test was the effective throughput and the throughput shown in the figure is the value at which 100%

of the transmitted packets were received. It follows from this result that vehicular applications aiming to achieve PDR close to 1 should not send at rates higher than those in Fig. 4a. The CBR results obtained for communication at maximum achievable throughput show that CBR decreases as the MCS rate is increased from 3 Mbps at R12BPSK to 27 Mbps at R34QAM64. As the MCS rate is increased, the probability of channel congestion and packet collision decreases resulting in lowered channel utilization. Additionally, higher MCS rates result in reduced transmission time even as message sizes increase which is evident in the decrease in latency shown in Fig. 4a with increasing MCS rate. The default transmitting rate of 10 packets/second was used for the latency test. Results in Fig. 4a are consistent with those found in [9].

b) Impact of priority queuing: Fig. 4b shows the impact of priority queuing on application latency. The first result illustrates how priority queues used for different applications impact their latency. The latency shown in this result is observed for the application instance receiving packets sent using *best effort* (BE) queue while another application instance sends packets using *background* (BG), *best-effort*, and *video* (V) priority queues successively. It is observed that latency for the packets using *best effort* queue increases as the priority of the queue being used by the second application increases. In EDCA, the different queues undergo internal contention when selecting a packet for transmission. The selected packet from this process then encounters channel contention [17]. Both internal and channel contention are based on queue priority. This results in packets utilizing relatively lower priority queues observing higher latency as the packets in higher priority queues get transmission priority. The second result in Fig. 4b indicates the impact of queuing delay as the aggregate load on the communication channel approaches 100% utilization. From Fig. 4a, the maximum achievable throughput at MCS rate R12QPSK for a 368 bytes message is 3 Mbps. As the number of vehicles sending at a rate of 3 Mbps increases, the channel utilization approaches 100% and the ensuing contention process for transmission results in prohibitive latency. This latency value has an upper bound contingent on the maximum queue capacity and can not increase beyond that. As a part of our future work, we plan to further investigate factors impacting queuing delay such as the queue drop policy and the queue limits.

c) Comparison with simulation results: Tests in Fig. 4c were conducted using both the hardware and simulation setups.Two tests were conducted: one showing the latency with increasing Tx-Rx communication range between 2 vehicles; and another showing latency as the message size increases with the fixed MCS rate and an aggregate load of 10 vehicles. As the Tx-Rx communication range increases, propagation delay between vehicles is expected to increase. The impact of propagation delay on end-to-end delay is expected to be significant when overall aggregate load is increased. Thus, it is observed that results from the first test in Fig. 4c show negligible latency difference, while those from the second test show significant variation in latency. Additionally, latency observed using the hardware setup was found to be ≈1 msec
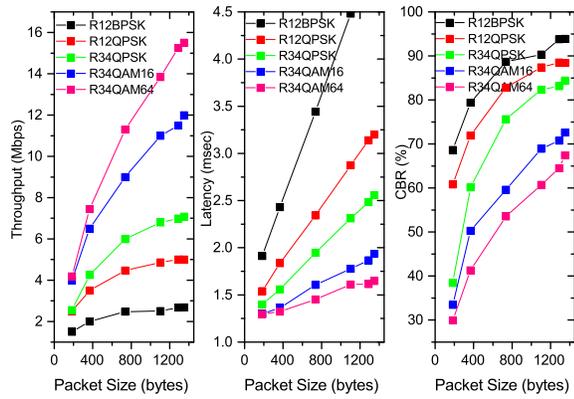
(a) Throughput, latency and channel busy ratio under varying packet sizes and MCS rates from hardware setup.
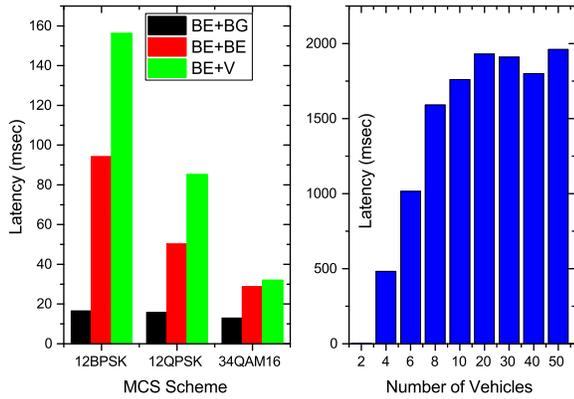
(b) Latency with different MCS rates and priority queue settings, and varying number of vehicles with channel utilization approaching 100%.
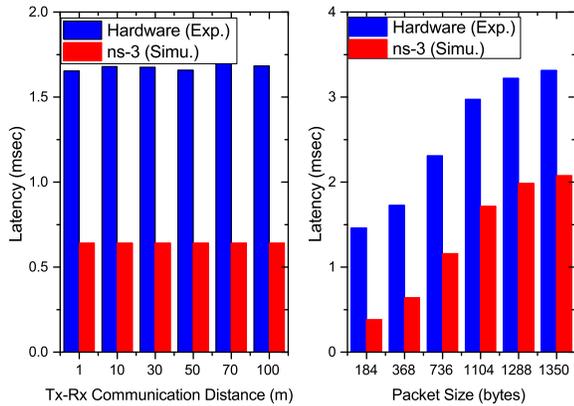
(c) Latency with different communication distance (for 2 vehicles) and constant message size (368 bytes), and different packet sizes (for 10 vehicles) for MCS rate of R12QPSK with sending rate of 10 Hz.

Fig. 4. Experimental results from hardware setup and comparison with simulation results.

higher than that observed in both mobile and non-mobile simulations. While it can be claimed that the consistent nature of the latency variation is indicative of an implementation difference in the two environments, further investigation is required to validate this claim.
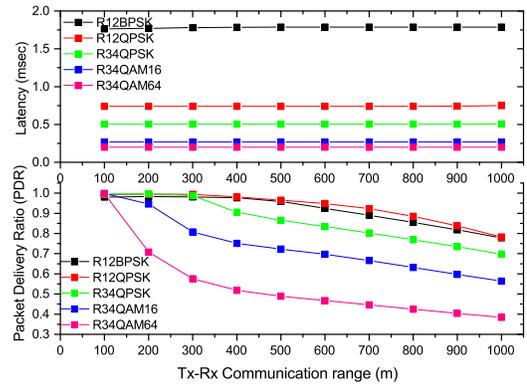

Fig. 5. Impact of different MCS rates on latency and PDR using default settings in mobile simulation environment.
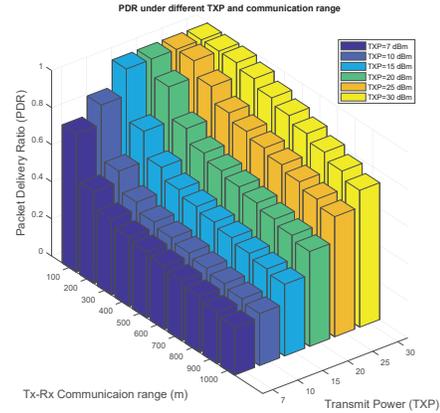

Fig. 6. Impact on PDR for varying transmit power values and Tx-Rx communication range using default settings in mobile simulation environment.

B. Experimental results from simulation tests

a) Impact of different MCS rates and Tx-Rx communication range: Latency and PDR have an inverse correlation with respect to increasing MCS rates. Fig. 5 shows that while latency decreases as the MCS rates increase, the PDR for higher MCS rates lowers as the Tx-Rx communication range is increased. The larger packet loss observed at higher MCS rates can be attributed to the increased probability of channel symbol error at higher modulations. The observed result suggests that lower MCS rates (e.g., R12QPSK) are recommended while transmitting at higher communication range, while higher MCS rates (e.g., R12QPSK) are advisable for shorter communication range where higher transmission rates are required. We observe trivial difference in latency as Tx-Rx communication range increases for a given MCS rate owing to reasons discussed in Section IV-A.3.

b) Impact of transmit power and Tx-Rx communication range: Fig. 6 shows the impact of transmit power and Tx-Rx communication range on the packet delivery ratio (PDR) using default settings. As observed in Fig. 5 also, PDR is higher for shorter Tx-Rx communication ranges for a given transmit power. Additionally, Fig. 6 shows that as the transmit power (TXP) value increases, the PDR (reliability) becomes higher
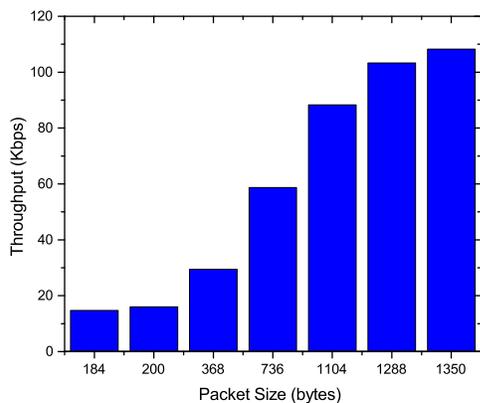
Fig. 7. Impact on throughput for varying packet size with MCS rate of R12QPSK and 60 vehicles.

at greater Tx-Rx communication ranges. With increasing Tx-Rx communication range, the probability of receiving weaker signal at distant nodes increases the packet drop probability. As TXP increases, this probability becomes lesser resulting in lower packet drops and higher PDR. Our testing indicates that TXP of 30 dBm allows maximum PDR at greater Tx-Rx communication ranges (>400 m).

c) Impact of packet size on throughput: Fig. 7 shows the impact of increasing message sizes on throughput observed over 60 vehicles for a given MCS rate. Consistent with results discussed earlier, increasing the message size increases the throughput at the receiving vehicle with our default simulation settings.

V. CONCLUSION AND FUTURE WORK

In this work, we have studied the impact of parameters within the DSRC stack on overall network performance. The simulation and experiment results suggest that higher MCS rates (e.g., R34QAM64) provides higher throughput, lower latency and lower CBR, but cannot achieve higher reliability (PDR) for distant receivers. In contrast, lower MCS rates (e.g., R12BPSK) can achieve higher reliability for distant receivers but at the expense of lower throughput, higher latency and higher CBR. A mid-level MCS rate (e.g., R34QPSK) can be said to provide a balanced performance results. Moreover, while increasing the message size within any MCS rate increases the throughput, it also increases the latency and CBR. Our findings also indicate that reliability over longer communication ranges can be increased with the use of higher transmit power. All these factors can be taken into account with respect to an application's requirements to ensure optimal network performance. In addition to this, the choice of priority queues utilized within an application or within the network can dictate the overall performance. This information can be applied at a network level to ensure that messages from safety-critical applications use priority settings that provide the lowest possible latency. We also illustrate the impact on performance as network utilization approaches 100% and find that network latency becomes prohibitive for vehicular application function at this point. This information is especially of interest while

designing multimedia and entertainment vehicular applications which are expected to be resource intensive.

Although we limit the results described in this paper to today's current V2X system that involves a WAVE/IP environment operating in a DSRC network, our broader goals are to explore the intersection of CAVs with low latency networking concepts that have seen renewed interest by the internet community to better support emerging cyber-physical systems that must operate 'out in the wild'. In continuing work, we plan to apply the understanding of network behavior gained from this study in designing systems that support lower latency. For this purpose, our future work includes development of a network-wide optimization scheme implementable via an infrastructural node that can dynamically adjust control metrics within a vehicular network to optimize the overall performance.

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