An Experimental Investigation of Multi-Hop V2V Communication Delays using WSMP

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***Abstract*—Even though there is an ongoing push by the U.S. government to adopt the Dedicated Short-Range Communications (DSRC) technology for intelligent transportation systems (ITS) applications, there is not sufficient real-world experimental data available that testifies the reliability of this technology when multi-hop communication is taken into consideration. The current protocol standards for DSRC, as defined by IEEE 1609.3, is purposefully not designed to provide support for multi-hop communication using WAVE short message protocol (WSMP). Instead, the WAVE protocol stack provides an alternate option for multi-hop communication using IP-based communication. However, most off-the-shelf DSRC devices only support WSMP-based broadcasts. Hence, the routing and forwarding services on WSMP are unavailable. Our current research attempts to implement the multi-hop forwarding services on top of WSMP as a cross-layer implementation. In this paper, we examined the challenges and performances of multi-hop vehicle-to-vehicle (V2V) communication in terms of packet drop rate and intra-nodal forwarding delay. Field experimental results with three vehicles show that nodal processing delays within the relay node consistently range from approximately 1 to 5.6 milliseconds. Our results further illustrate the effect of line-of-sight and inter-nodal distances on packet transmission success.**

I. Introduction

The United States Department of Transportation (USDOT) and the Intelligent Transportation Systems Joint Programs Office (ITS JPO) have recently increased the focus on connected vehicles research using DSRC (Dedicated Short-Range Communications), as a viable option for improving safety and providing other services for road users. DSRC, as defined by IEEE 801.11p and IEEE 1609.x, is a two-way wireless communication medium used for data transfer between multiple vehicles or between vehicles and infrastructure. DSRC devices installed in vehicles are called On Board Units (OBU), while those deployed on the streets are known as Road Side Units (RSU). The OBU continuously shares the information of its location, bearing, speed, and acceleration with other equipped vehicles and RSUs through basic safety messages (BSM) that are in reachable within communication range, typically varying between 300m to 1000m depending on urban or freeway environments. The focus of the USDOT on researching DSRC and its adoption by major auto manufacturers made it highly probable that DSRC will eventually be available in most newer vehicles. This makes it paramount to investigate the performance of DSRC with field tests.

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Connected vehicle (CV) technology enables a wide array of services, such as safety, business, and entertainment applications. A few examples of safety applications are blind spot warning, hard braking ahead warning, cooperative freeway merging [1]–[3], and forward collision warning signals. Examples of non-safety applications include various dynamic mobility applications such as, integrated dynamic transit operations [4], dynamic ride sharing, taxi hailing [5]–[7]. CVs must provide fast association between nodes and low latency to guarantee reliability for safety applications and quality of service for user oriented applications such as streaming. For full connectivity of all vehicles in a V2V configuration, it is important for payloads to be able to traverse multiple nodes in the network through multi-hop communication [8]–[17].

However the current protocol standards for DSRC, as defined by IEEE 1609.3, is purposefully not designed to provide support for multi-hop communication using WAVE short message protocol (WSMP). Instead, the IEEE 1609.3 protocol stack provides an alternate option for multi-hop communication using IP-based communication. Most off-the-shelf DSRC devices only support WSMP-based broadcasts. Hence, the routing and forwarding services on WSMP are unavailable. To enable routing on WAVE, our current research attempts to implement multi-hop forwarding services on top of WSMP as a cross-layer implementation.

In this paper, we examined the challenges and performances of multi-hop vehicle-to-vehicle (V2V) communication in terms of packet drop rate and intra-nodal forwarding delay.

The rest of the paper is organized as follows. Section II describes prior literature on experimental studies conducted on V2V communication using various wireless technologies. Section III discusses some of the challenges associated with multi-hop V2V communication. Section V describes our experimental environment followed by the results in section VIally we conclude in section VII with our future plans on extending this research.

II. Related Work

[18]–[20] described some of the earlier field experiments on connected vehicles using commodity 802.11 devices. These experiments used 802.11b, which operates in the ISM band. Thus, the experiments lacked adaptability to the particular requirements of a real ad hoc network. Specifically, the need for safe, fast, and reliable data transmission in a fast changing and unstable network [21]. IEEE has introduced the 802.11p

protocol with changes to the frequency spectrum, MAC, and physical layer from 802.11a with the intention of addressing most of the communication issues [21]. Unfortunately, since its introduction into the market, there has been a lack of field experimentation on 802.11p's multi-hop characteristics in existing literature.

In [21], comparisons of 802.11 and 802.11p show that adjustments made to cope with the dynamic nature of Vehicular Ad hoc Network (VANET) have positive results. In a simulation, using a reactive protocol (Ad Hoc On-Demand Distance Vector) for routing, authors measured metrics like delay, packet drop, and throughput, and found that 802.11p outperformed 802.11 in all scenarios.

Bai et. al [22] investigated the packet drop rate of 802.11p as it is affected by various factors like distance, velocity, radio signal strength, and transmission power. DSRC compatible radio antennas were used on 802.11p with adjustable transmission power and data rate, a high accuracy GPS receiver, and a DSRC protocol stack that is configured to broadcast messages every one hundredth of a second. Vehicles followed each other at varying speeds and distances. The authors contend that there is a "gray zone phenomenon" applicable to DSRC according to the measurements, as is present with all wireless sensor networks. This means that the probability of dropping packets is never 0%. Thus, application designers will always have to provide error compensation in applied protocols. The distance between sender and receiver and the signal propagation environment affected the packet drop rate and other characteristics. Authors show that as the distance increased, packet drop increased. This is consistent with results obtained in 802.11b experiments in [18] and [20]. To measure the effects of the environment, the authors performed experiments in urban freeway, rural freeway, rural road, suburban road, and open field. Multipath fading, and a sharper rise in packet drop rate was observed in all experiments, except for the suburban road and open field settings due to the lack of objects that cause blocking and signal reflection. The experiments also conform to those on 802.11b experiments on the relationship between velocity, radio signal strength, and transmission power to packet drop. The authors found that velocity has no cumulative effect, radio signal strength increases caused decrease in packet drop, and increase in the transmission power resulted in slight reduction in packet drop.

Other researchers have also experimented with 802.11p protocol with a view to gain much needed insight into the characteristics that will affect deployment of technologies on it. Shagdar et.al. [23] carried out extensive tests in an attempt to gather information for future IPv6 deployment. The authors contend that IPv6 will enable the convergence of different networks, wireless and wired, so it is important to assess its performance in a VANET. It is claimed that although IP layer execution might be disabled in safety critical payloads because of delay, infotainment applications will require it. The authors used one vehicle fitted with an OBU and a RSU mounted on a pole. The experiments were carried out on a 1.6km stretch of straight road, with the RSU placed at 400m from the start sending payloads periodically. Their experimental results concur with other experiments in terms of same correlation between the packet drop rate, received signal strength, and distance. It is also discovered that the data rate has an effect on the packet drop, especially at large distances. Thus, there will be a benefit in making protocols adjust data rates with relative distance to the data source or receive signal strength.

With the aim of determining how various parameters such as delay, packet loss, and jitter are affected by different WAVE channel conditions in DSRC, Vivek et. al. performed numerous outdoor experiments [24]. Experimenters utilized one RSU mounted on a 6m pole, two OBUs mounted on separate cars, and a 600m road as a test bed. The two types of channel available in the DSRC are SCH (service channel) and CCH (control channel). The results of the tests carried out show that packet loss, delay, and jitter were always higher for SCH packets. For both channels, the packet loss increased as distance increased in the experiments. Transmission quality also degraded sharply at 200m, a phenomenon the author's claim was caused by environmental issues in the form of a decreased elevation in the middle of the test bed causing loss of LOS. Delay and jitter, however, did not alter significantly due to distance or the environment.

III. Multi-Hop Communications & Challenges

Multi-hop broadcasting is performed via packet forwarding and is necessary for intelligent transportation systems because safety or service-related messages may need to travel outside the original transmission range of the messages [25]. Multi-hop broadcasting, in its simplest sense would consist of nodes rebroadcasting messages upon reception of the messages [26]. This leads to a broadcast storm, in which the network is swamped with redundant rebroadcasts [26]. Flooding without proper control leads to several network problems, such as failure to scale properly and packet collision [25]. Packet collision can occur when multiple nodes attempt to send messages simultaneously and can cause packets to be discarded. Uncontrolled flooding is not scalable because the network quickly becomes over-burdened with redundant messages [25].

Another problem with multi-hop communication is hidden node problem which affects VANETs. This problem occurs if a vehicle is visible to an access point, but not to surrounding nodes [27]. Additionally, the IEEE 802.11p standard does not include packet receipt confirmation, which is an issue for safety-related systems that need assurance of message delivery [27].

Multi-hop V2V communication is inherently complex because VANETs are unstable and large in scale [27]. Additionally, VANETs are heterogeneous and cannot have a fixed global topology definition [28], [29]. Additionally, communication ranges vary based on location and environment [29]. While DSRC can potentially achieve a communication range of 1000 meters in freeway environments, this range can suffer greatly based on physical obstructions in urban environments, dropping the range to fewer than 100 meters [1], [9], [28], [30].

An additional challenge unique to VANETs is the possibility of frequent disconnections or gaps in communication [29]. Because of the high mobility of nodes, particularly in high-speed highway situations, connections are intermittent and disconnections are to be expected [29].

Intra nodal processing delay associated with forwarding packets within the intermediate relay nodes can also pose problem in a multi-hop communication. Very few experiments have been conducted to investigate intra-nodal processing delay. Hoque et. al. [31] conducted experiments with multi-hop wireless networks using 802.11b, where the intra-nodal processing delay, on the average, ranged from a few micro seconds to hundreds of micro seconds and was found to be proportional to payload size.

IV. Cross-Layer Protocol Design

To investigate multi-hop V2V communication using WAVE short message protocol (WSMP) this research endeavored to implement multi-hop forwarding services on top of WSMP as a cross-layer implementation. One obstacle was that WSMP does not use IP addresses for communication. In order to implement forwarding services on WSMP, we used MAC addresses of the OBUs to identify the source and destination. The WSMP layer in 1609.3 is a combination of network layer (layer-3) and transport layer (layer-4) in the OSI protocol stack. We utilized the MAC address from the Link layer (layer-2) and encapsulated along with other header fields (as described by the Fig. 1) within the payload of WSMP. The details of the cross-layer protocol implementation and the forwarding algorithm will be described in a separate work.

V. Field Experiments

Real-world experimental multi-hop V2V transmission data is limited. The goal of this experiment is to provide insight into real-world delays and packet drop rate that can aid further research.

This experiment took place at the parking lot of East Tennessee State University Innovation Lab and on West Market St. in Johnson City, TN. The vehicular ad-hoc network setup was limited to three nodes: each using Arada Systems LocoMate Classic OBUs as the DSRC transceivers Fig 1. An OBU connected to a laptop via Ethernet using Telnet protocol was located inside of each vehicle for manual execution of the program used. The program used allowed the user to send a DSRC message with text entered by the user as the payload. Each message contained the MAC address of the receiver, the

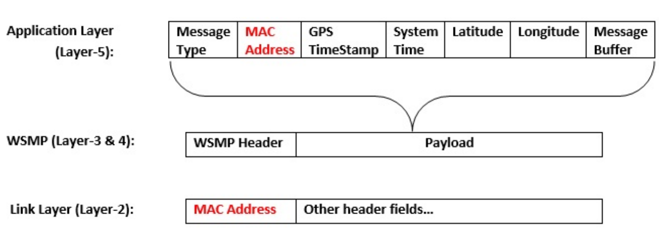

Fig. 1: Cross-layer protocol implementation

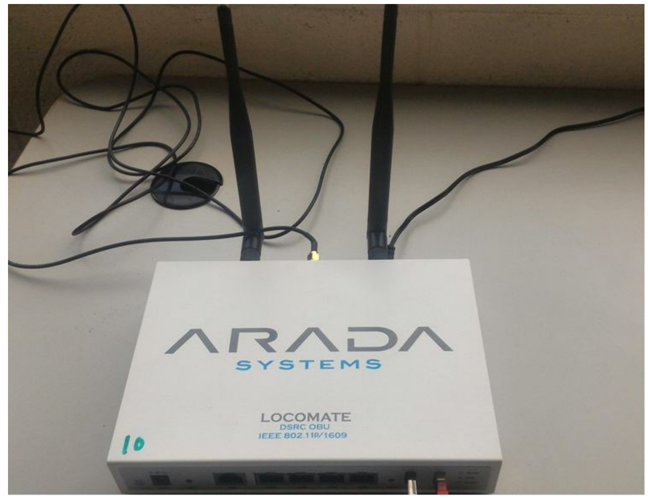

Fig. 2: ARADA On Board Units used for test.

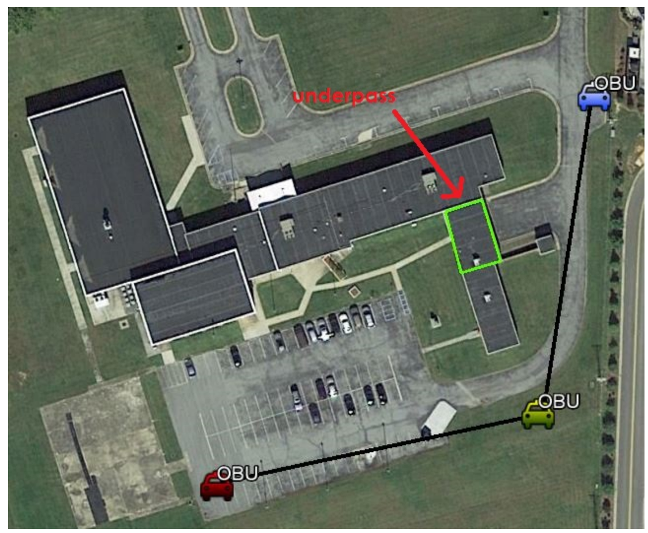

Fig. 3: Static Test 1 and 2

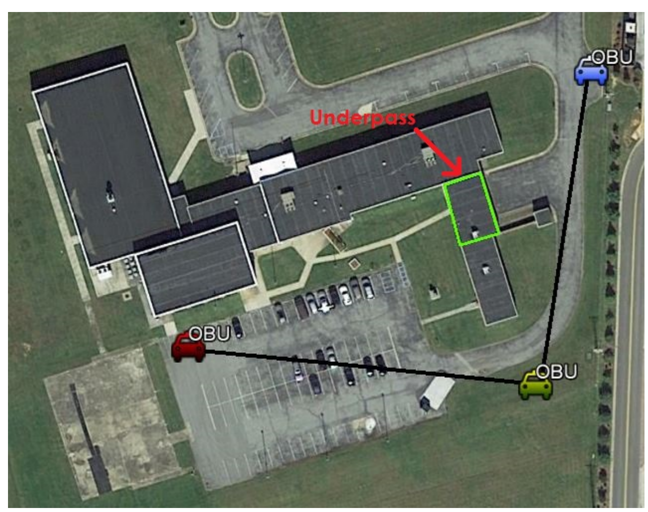

Fig. 4: Static Test 3, 4 and 5

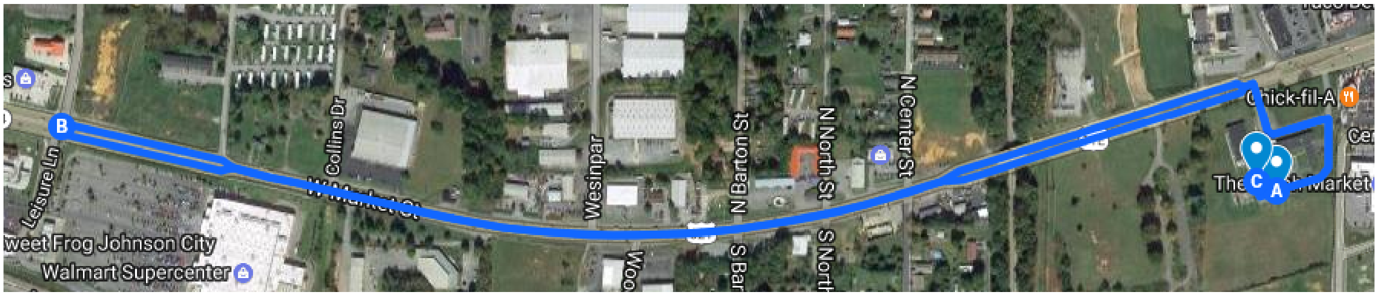

Fig. 5: Mobile Tests.

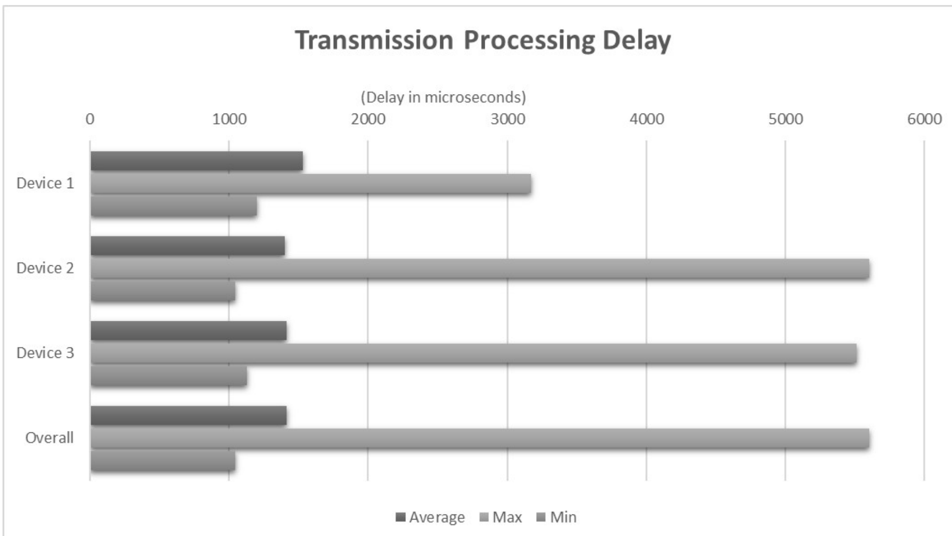

Fig. 6: Nodal processing delay within intermediate (relay) nodes

TABLE I: Static Position Transmission Results.

	Tx's	$1 \rightarrow 2$	$1 \rightarrow 2 \rightarrow 1$	$1 \rightarrow 2 \rightarrow 3$	$1 \rightarrow 3$	$1 \rightarrow 3 \rightarrow 2$	$1 \rightarrow 3 \rightarrow 1$
Test 1	10	10	10	10	2	2	2
Test 2	11	11	11	11	5	5	5
Test 3	20	20	20	20	0	0	0
Test 4	20	20	20	20	0	0	0
Test 5	20	20	20	20	0	0	0
Successful Tx	81	80	80	79	7	7	7
Success %		98.8	98.8	97.5	8.6	8.6	8.6

TABLE II: Mobile Position Transmission Results.

	$1 \rightarrow 2$	$1 \rightarrow 2 \rightarrow 1$	$1 \rightarrow 2 \rightarrow 3$	$1 \rightarrow 3$	$1 \rightarrow 3 \rightarrow 2$	$1 \rightarrow 3 \rightarrow 1$
Successful Tx	127	121	103	105	94	100
Success %	96.2	91.7	78.0	79.5	71.2	75.8

TABLE III: Transmission Processing Delay in microseconds.

	Average	Max	Min	Number of Tx's
OBU 1	1533	3171	1198	8
OBU 2	1400	5605	1047	140
OBU 3	1413	5510	1128	257
Overall	1411μs	5605μs	1047μs	405

MAC address of the message origin, GPS coordinates of the last sender, and a relay number that indicated whether the sender was the origin or the first hop. Each message also contained a time stamp. However, the OBUs' internal clocks were not properly synchronized. Each message was limited to one hop. The intermediate node also output the internal processing delay on the scale of microseconds.

In order to assess packet delivery success rate, a laptop user sent messages containing consecutive number counts. Packet loss was determined by skipped numbers in the receiving OBU's log of the messages.

A total of five static tests were conducted with end devices in approximately 80m from the intermediate relay node (Fig.

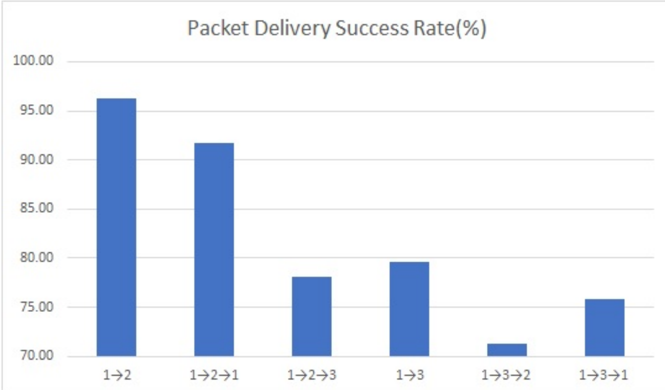

Fig. 7: Mobile Experiment PDR.

3 and Fig. 4). To determine the appropriate spacing of the vehicles, a non-multi-hop message was broadcast from an endpoint while the other endpoint continued to move until the simple broadcast was no longer received. This decreased the likelihood that a multi-hop message would successfully transmit between endpoints. For count 3, 4, and 5 one vehicle was repositioned closer to the nearby structure completely eliminating line of sight to the opposite endpoint as shown in Fig. 4, while both endpoints (node 1 and 3) retained line of sight with node 2. Vehicle spacing for tests 1 and 2 is shown in Fig. 3.

A mobile experiment was done while all three vehicles followed the approximately 3.77 km route shown in Fig. 4. Each driver attempted to maintain a distance of 50m. However, at the beginning and end of the mobile transmission counts, all three vehicles were in much closer proximity. This was unavoidable as the route was not closed to traffic.

The processing delay data consists of 405 data points obtained from the OBUs when used as the relay node. The five static position transmission counts resulted in 81 transmission records. The mobile transmission count resulted in 132 transmission records.

The experiment was constrained to three nodes by the availability of participants and compatible OBUs. The lack of synchronization of the OBU's internal clocks also limited interpretation of the data gathered. The packet delivery rate for the mobile experiment is shown in Fig. 7.

VI. Results

Transmission processing delay resulted in an overall average of 1411 μs, maximum of 5605 μs, and minimum of 1047 μs. Further processing delay results for each OBU are shown in Table III and in Fig. 6.

Communication between three nodes, with 1 being the origin, 2 being the intermediate node, and 3 being the endpoint, results in 6 different possible routes: $1 \rightarrow 2$, $1 \rightarrow 2 \rightarrow 1$, $1 \rightarrow 2 \rightarrow 3$, $1 \rightarrow 3$, $1 \rightarrow 3 \rightarrow 2$, $1 \rightarrow 3 \rightarrow 1$. For example, $1 \rightarrow 2 \rightarrow 1$, indicates successful transmission from origin to intermediate back to origin. The success rate of each of these routes is shown in Table I and Table II for the static position and mobile position experiments, respectively. Fig. 5 is a graphical representation of Table II.

VII. Conclusions

Processing delay results were relatively consistent across all three OBUs. Delay times are likely negligible in almost all scenarios as minimum human reaction time is well below the maximum processing delay [32]. Further experimentation including a variety of DSRC capable devices is needed.

It is suggested that the higher transmission success rates during static tests 1 and 2 compared to those of 3, 4, and 5 were due to less line of sight obstruction for routes $1 \rightarrow 3$, $1 \rightarrow 3 \rightarrow 2$, $1 \rightarrow 3 \rightarrow 1$, as shown in Fig. 2 and Fig. 3. Further experimentation should more carefully consider line of sight issues to eliminate contributing variables.

The mobile transmission success data is largely anecdotal as distances between vehicles were not maintained. The orientation of the vehicle is also probable to have influenced the success rate due to variable signal penetration through different parts of the vehicles. It is suggested that an OBU antenna external to the vehicle would minimize this factor. Future studies of mobile multi-hop connected vehicles will need to find ways to address both of these issues.

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