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# An Efficient Vehicle-to-Everything (V2X) Communication Algorithm for the Deployment and Operation of Self-driving Cars

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**ABSTRACT**

**The deployment and implementation of self-driving cars (SDC) is becoming a reality. Various units and subsystems of the SDC ecosystem are needed to be impeccable in their executions. It is therefore relevant to have communication subsystem for transmitting information from Vehicle-to-Everything (V2X) which is useful in efficient implementation of the SDC technology. However, the heterogeneous and dynamic environments and overall ecosystems pose a reliability challenge on the information transmitted to be processed by the central processor for efficient communication decision of the SDC in the vehicular environments. This study demonstrates a proposed solution by examining and providing a SDC communication model and an algorithm that can enhance the operation of the SDC. The model considers the impact of vehicle speed, delay on information transmitted, radio frequency, and vehicular environments which are incorporated into the SDC decision making software. The proposed approach is compared with theoretical model and existing study. The results show that the proposed algorithm is about 95 % efficient at an average speed of 30 mph with a processing time less than $1ms$ and less than $1\mu s$ delay on information transmitted in a highly signal impacted SDC complex environment case. It also shows about 99 % efficient at an average speed of 70 mph in a less signal impacted SDC complex environment case. This proposed approach could be used to design the communication capability of on-board Vehicle-to-Everything devices and for efficient planning and future deployments of SDC.**

Keywords - **Decision making, Energy per bit to noise, Propagation model, Self-driving cars, Vehicle-to-everything communications**

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## 1. INTRODUCTION

The implementation of self-driving cars (SDC) technology is one of the on-going efforts by researchers, automakers, and high technology companies (HTC) to improve the safety operation of terrestrial or land transportation systems. However, there are various identified challenges that would impact the performance of SDC deployment [1], [2], [3]. To start with, one factor that will enhance the operation of SDC is the interconnectivity among the vehicles and all other things in the environments. The SDC subsystems which, are made up of sensors, communications devices, and central processing unit, are deployed on the cars and in the environments to sense the environments and send information to central processing unit locally or remotely for processing and make decision. However, the complex ever-changing SDC environments will impact the information transmitted within SDC ecosystem. The SDC technology could be designed to communicate with everything in the vehicular environments. Considering the components of SDC environments, such as cars of different kinds, road signs and sign stands, pedestrians, road lanes, pavements, images of different kinds, buildings, etc., all of these may impact the communication signals in Vehicle-to-Everything (V2X) Communications. In December 2016, the U.S. Department of Transportation (DOT) announced a proposal to mandate a groundbreaking new technology – Vehicle-to-Everything (V2X) Communications. V2X communication is subdivided into vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-pedestrian (V2P), vehicle-to-home (V2H), vehicle-to-network (V2N), vehicle-to-cloud (V2C), vehicle-to-environment (V2E), and vehicle-to-things (V2T). V2X communication is going through different phases to be specifically defined and designed for SDC technology implementation. As of June 2019, DOT is requesting for comments and implementation design for V2X communication from researchers, developer, and general public [4]. A test conducted by Mcity for V2V and V2I (self-driving shuttles) shows that interconnectivity among self-driving shuttles will make them efficient [5]. Also, the NXP in 2021 has designed a referenced chip for V2X communication demonstration. It is stated that V2X will enhance positioning, safety, and connectivity. Hence, the V2X communication can be implemented for SDC and make them efficient as well.

Most of the discussions on V2I are using simulation and presenting performance analysis with various V2V and V2I communication protocols and theoretical models. The majority of the existing studies simulate the V2I and V2V using LTE communication protocol and consider LTE latency without considering the impact of the speed of vehicles, delay on information transmitted, radio frequency (RF), and vehicular environments which are modeled into SDC decision making software. The existing articles discuss the application of various communication protocols for V2V and V2I. Among such protocols are LTE, IEEE 802.11P [6], [7], [8], [9], [10], [11], [12], [13]. Other protocols used for device-to-device (D2D) or V2V, V2I communication are LTE-M, LTE-NBIoT, IEEE 802.15.4 – ZigBee, and so on. Likewise, the intelligent transportation system (ITS) department of US DOT presents a discussion on Dedicated Short-Range Communications (DSRC) as option for V2V or V2I communications. DSRC is intended for highly secure, high-speed wireless communication between vehicles and the infrastructure. Also, National Highway Traffic Safety Administration (NHTSA) states that US DOT seeks input on testing vehicles with automated driving systems technologies. However, the novelty or an advantage of this proposed study is that it is applicable to any type of communication protocols and it is also independent of any hardware transceiver (Tx/Rx) and its specifications used.

Furthermore, theoretical propagation models (such as free space) have been used in the prediction and implementation of existing V2I and V2V studies. The theoretical propagation model does not consider the complex heterogeneous environments for the SDC operations. It has been shown in literature that such model is not efficient [14], [15], [16], [17], [18], [19]. Similarly, in the implementation of the communication model, the theoretical model is not incorporated into the SDC decision making software. Hence, SDC decision making software for V2X communication may not be efficient or available and could lead to wrong SDC V2X communication decision on some occasions. Moreover, the dynamic components of the SDC ecosystem cause degradation on signal transmitted by scattering, diffracting, absorbing, penetrating, or Doppler shifting of the signal wave and energy. The recoverability of information bits at the receiver (that is, with good signal-to-noise ratio-SNR) is a concern. In the same vein, the decision making by the SDC when reaching total automatic cruise control for V2X communication could be determined by the quality of transmitting the information back and forth to the central processing unit to make quick decision. The decision making is as good as the data obtained and transmitted within the subsystems (algorithms- software and hardware) that will process the information and make ultimate judgment on V2X communication.

In addition, some factors such as speed of vehicles, delay on information transmitted, radio frequency (RF), and vehicular environments that could determine the V2X communication operation efficiency of SDC are not considered in some of the simulation of V2X-V2V communications. These shortcomings could impair efficient transmission of information within the SDC ecosystem and communication decision output of SDC decision making software. There is no demonstration or tested SDC using the proposed V2X communication algorithm in this proposed study. Similarly, Codha wireless and QUALCOMM (9150 C-V2X chipset) [20] use 802.11p for C-V2X-V2I capability solution and testing. When the SDC makers eventually start to use holistic V2X communication protocol, there will be a need to have an efficient V2X communication models and algorithms that are incorporated into the SDC decision software for smart communication decision. The aim and contribution in this proposed study is geared towards providing such analysis and algorithm; and demonstrating the solution that will support the operation of SDC more efficiently and reliably.

The remainder of this paper is organized as follows: Section 2 covers the literature review. Section 3 provides the proposed reliability model, SDC V2X algorithm and the description of the vehicular environments. Section 4 contains the discussion about the demonstration of results and validations. Section 5 gives the conclusion and future study.

**Summary of Contributions:**

i. The study proposes how to design and implement holistic V2X communication for interconnectivity in the SDC environments that will enhance the operation and deployment of SDC technology. The proposed approach is useful because of the changing SDC environments.
ii. The study proposes SDC V2X communication algorithm (and equation) considering multiple vehicular environmental impacts and car parameters. The algorithm (model) is incorporated into the existing SDC central decision software which will improve the operation of SDC more efficiently and reliably.
iii. The proposed approach is applicable to any type of communication protocols/standards (e.g. 5G NR C-V2X (PC5) standard, PC5 (direct communication mode), and yet to be developed. It is also independent of any hardware transceiver (Tx/Rx) and its specifications used. That is, it applies appropriately to the respective protocols and hardware parameters.
iv. The proposed approach could be used to design the communication capability of on-board V2X devices for efficient planning and future deployments of SDC.

## 2. RELATED WORK

The authors in [6] present a simulated study using Riverbed modeler to test the performance in term of packet loss rate, LTE response time, end-to-end delay and handover delay of manned and unmanned car connectivity using LTE communication protocol. It is stated in the paper that end-to-end delay for V2V or V2I is between 0.628ms to 1.41ms for a speed less than 37mph but in the study, free space model is used for prediction. Therefore, they do not consider environmental impacts and communications for holistic V2X communications. The efficiency of V2I and V2V information bits in term of SNR level is not tested. Also, the study does not formulate any efficient model or algorithm that is incorporated into SDC decision making software.

Similarly, there have been a lot of empirical studies and data about path loss models for tiny wireless sensor network (WSN) deployment in various environments and

IoT applications including road and parking lots [15], [16]], [21], [22], [23], [24], [25]. These empirical propagation models are proven to be more suitable in describing a typical propagation environment. However, there is no enough study or analysis on the integrity of information communicated in V2X communication considering the impact of the speed of vehicles, delay on information transmitted, radio frequency (RF), and vehicular environments which are incorporated into SDC decision making software using the empirical models. The study in [25] shows a derived V2V success probability near an urban intersection for V2V communications. Also, the study in [24] proposes slope path loss model for V2V communication and check the accuracy of the model with actual measurements in on-slope area of road. The study [26] proposes the tuned free-space path loss modeling in high-speed railroad considering Doppler Effect. The study investigates the propagation model considering Doppler Effect by using measured data of high-speed railroad at viaduct and plain in the free space and proposes a tuned free-space path loss modeling. The authors report that the estimated model is almost like the tuned free space path loss model. Likewise, this paper [27] presents the studies of indoor radio wave propagation models with Doppler frequency shift effect using free space and log-distance propagation models to analyze indoor propagation problem. The authors report the received signal strength indication (RSSI) and path loss values in form of graph for moving object at constant speed receiving signal from transmitter in indoor environment. Also, the authors in [28] present measurement and analytical results for V2V propagation path loss and root-mean-square delay spread along the roadway. They [28] find the Doppler shift effect in a simulation scenario. The study in [28] proposes a simulation for the path loss and blockage loss in frequency band above 6 GHz V2V communication in urban grid and highway as well. The authors state that the path loss value increases with the increasing in the carrier frequency, which affects the performance of the system. However, this is expected. Likewise, the study [29] shows the design of a fine-grained TDMA-based MAC protocol to support ultra-reliable broadcast for AV. The authors [29] present a simulation scenario to verify the effectiveness of the proposed TDMA-based MAC protocol. The study [30] proposes a collaborative code dissemination (CCD) approach with two-way V2X paradigm by using vehicles act as code to disseminate code with fast and low-cost style for urban computing [31]. The authors perform experiment to verify the performance of the approach and results shows a 68.4 % improvement compared to the existing one. In addition, the study [32] summarizes the latest ongoing work in 3GPP, providing insight into the main developments in terms of the radio, network architecture, and application domains for 5G V2X Communications. Also, [33] presents the analysis of connected-car system and car-to-car C2C communications and the study in [34] describes the impact and significance of V2V and V2P communications. The report in [35] describes the analysis of V2X communication protocol and the advantages such as road safety, traffic efficiency, and energy saving for SDC implementations.

However, what is missing in literature is that there is no extensive study about providing both theoretical and empirical efficient communication model for holistic V2X incorporated into SDC central processing for the SDC operation. The proposed model and approach in this study could be used to design the communication capability of on-board V2X devices based on the speed of the vehicle and the surrounding environmental components. The proposed approach is modeled as the part of the SDC decision making software.

## 3. PROPOSED MODEL

### 3.1 Environment Descriptions and Communication Model

The vehicular environments and roads where the SDC would be deployed may consist of lanes, one-way and multi-way roads, road signs, safety barriers, fixed communication infrastructures, traffic intersections, buildings, and many other intersections. There could be walk ways for pedestrians and bicycle lanes. The traffic conditions- (type of vehicles, various road speed limits, unprecedented crash, various type of human drivers and pedestrians) make the SDC environment complex and dynamic. Consequently, the traffic conditions degrade communication signals and impair the efficiency and accuracy of information being transmitted in V2X communication. For simplicity, this study presents communication models for SDC deployment in two-way traffic scenario as shown in Fig 1. The model is applicable to multi-way roads and intersections. The impact of vehicle speed is derived geometrically considering the Doppler shit effect because of the vehicle speed and propagation delay of information from transmitting station (Tx) to receiving station (Rx)- (that is, V2V, V2I or V2P). The geometric diagonal or parallel distance between Tx and Rx due to angular shift of arrival ray of signal is modeled in the propagation model which in turn is modeled into SDC decision making software. There are theoretical propagation or path loss models such as free space and two-ray model which have been proved to be imperfect in real-life deployment [15], [36], [37], [38]. Path loss is the difference between the Tx and Rx power. The theoretical model could be used to provide alternative model where real-world environmental model is not available. A more realistic propagation model is the log-distance model that describes the impact of the dynamic SDC environments.

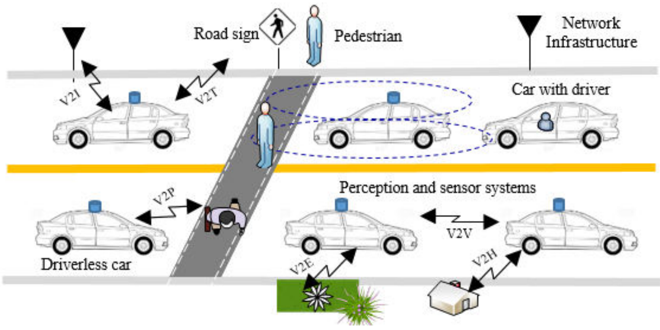


**Fig. 1. V2X communication system in two-way road.**

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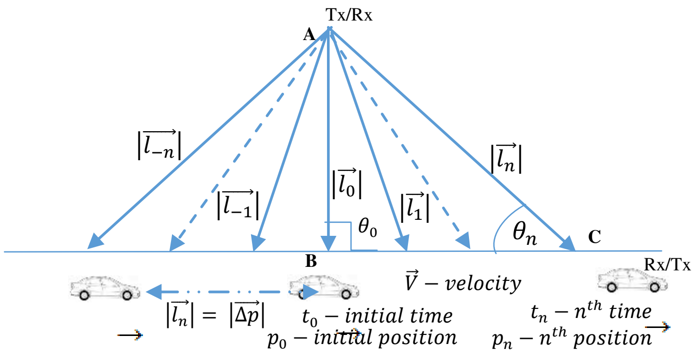


**Fig. 2. Moving car and shifted signal ray lengths.**

From Fig 2, displacement or change in position, $|\vec{\Delta p}|$

$$|\vec{\Delta p}| = p_n - p_0 \qquad (1)$$

change in time,

$$\Delta t = t_n - t_0 \qquad (2)$$

$l_0$, *initial signal ray length*, it is assumed to be equal to the height of infrastructure – fixed base station (BS). $t_0$ is the moment when the velocity direction is perpendicular from Tx/Rx to the car (Rx/Tx).

$|\vec{l_0}| \cdots |\vec{l_n}|$ – length of signal ray paths in meters.

$\theta_0$, angle of shift for initial signal ray length in degree.

$\theta_0 \cdots \theta_n$ – angle between direction of moving car and the $n^{th}$ arriving signal ray path

From Fig 2, considering ∠ ABC, and using trigonometry, for $\theta < 90^\circ$, that is,

$$\cos\theta_n = \frac{|\vec{\Delta p}|}{|\vec{l_n}|} \qquad (3)$$

Therefore, length of signal nth ray, $|\vec{l_n}|$

$$|\vec{l_n}| = \frac{|\vec{\Delta p}|}{\cos\theta} \qquad (4)$$

Also, from trigonometry,

$$\theta_n = \tan^{-1}\left(\frac{|\vec{l_0}|}{|\vec{\Delta p}|}\right) \qquad (5)$$

Consequently, $|\vec{l_0}| \cdots |\vec{l_n}|$ is assumed to be effective distance between the referenced station-Tx and target-Rx (vehicles, infrastructures, pedestrians, home, networks, environments, or things).

Similarly, from law of motions, if it is assumed that the car is moving at a constant velocity $\vec{V}$, therefore, the displacement is

$$|\vec{\Delta p}| = \vec{V} \times \Delta t \qquad (6)$$

Therefore, substituting (5) and (6) in (4), the effective distance between the Tx and Rx due to the car speed becomes, $|\vec{l_n}|$

$$|\vec{l_n}| = \frac{\vec{V} \times \Delta t}{\cos\left(\tan^{-1}\left(\frac{|\vec{l_0}|}{|\vec{\Delta p}|}\right)\right)} \qquad (7)$$

The effective distance, $|\vec{l_n}|$ is substituted into a propagation model. At $\theta_n = 0$, the effective distance between the Tx and Rx due to the car speed becomes $|\vec{l_n}| = |\vec{\Delta p}|$ (Fig. 2), that is, there is no shift or there is communication in V2X in straight-line-of-sight (SLOS) between Tx and Rx and relative speed between the moving vehicles is used.

In similar concept, the free space propagation model is given as [36], [37], [38]:

$$P_l(dB) = 32.44 + 20\log_{10} d(km) + 20\,log_{10} f(MHz) - gt - gr \qquad (8)$$

where $d$ is the distance between Tx and Rx, and $f$ is the frequency of operation, $gt$ and $gr$ are the Tx and Rx gain (dB) respectively.

Therefore, substituting (7) in (8), the theoretical propagation model, $P_l$ due to signal shift as result of car speed becomes

$$P_l(dB) = 32.44 + 20\log_{10}\left(\frac{\vec{V} \times \Delta t}{\cos\left(\tan^{-1}\left(\frac{|\vec{l_0}|}{|\vec{\Delta p}|}\right)\right)}\right)(km) + 20\,log_{10} f(MHz) - gt - gr \qquad (9)$$

Likewise, for a realistic model that considers the propagation environments is the log-distance model given as [15]

$$P_l(d)(dB) = P_l(d_o)(dB) + 10m\log_{10}\left(\frac{d}{d_o}\right) + X_{\sigma(dB)} \quad (10)$$

where $d_o$ is far - field distance or referenced distance (1m), $d$ is the distance between Tx and Rx (m), $P_l(d_o)(dB)$ is the median path loss at reference distance (1m), slope $= 10m$, $m$ is the path loss exponent, and $X_{\sigma(dB)}$ = lognormal shadowing. Lognormal shadowing is the Gaussian random variable with zero means, variance $\sigma_{(dB)}{}^2$, $X_{\sigma(dB)} \sim N(0, \sigma_{(dB)})$ and standard deviation $\sigma_{(dB)}$.

The variables $P_l(d_o)$, $m$, and $X_{\sigma(dB)}$ characterize and determine the SDC heterogeneous propagation environments impact per time (V2X vehicular) and are determined experimentally. They characterize the multi-path propagation effect as well. The standard deviation $\widehat{\sigma_{dB}}$ can be estimated from measured values by:

$$\widehat{\sigma_{dB}} = \sqrt{\sum_{i=1}^{z}\frac{\left(P_{lm_i} - P_{lp_i}\right)^2}{z-1}} \qquad (11)$$

where $P_{lm_i}$ is the $i^{th}$ measured propagation path loss value, $P_{lp_i}$ is the $i^{th}$ predicted path loss mean, and $z$ is number of samples [15], [39], [40].

Therefore, substituting (7) and (11) in (10), the experimental propagation model due to signal shift because of car speed and based on respective V2X communication becomes

$$P_{L_{(V2X)_j}}(d)(dB) = P_{l(V2X)_j}(d_o)(dB) + 10m_{(V2X)_j}\log_{10}\left(\frac{\vec{V}\times\Delta t}{\cos\left(\tan^{-1}\left(\frac{|\vec{l_0}|}{|\overrightarrow{\Delta p}|}\right)\right)}\right) + X_{\sigma(V2X)_{j_{(dB)}}} \quad (12)$$

Where $P_{L_{(V2X)_j}}(d)(dB)$ is the respective V2X path loss propagation model, that is, V2V, V2I, V2P, V2H, V2C, V2T, and $P_{l(V2X)_j}(d_o)(dB)$ , $m_{(V2X)_j}$ , $X_{\sigma(V2X)_{j_{(dB)}}}$ , are their respective V2X complex environmental impacts.

Some values for $P_{l(V2X)_j}(d_o)(dB)$ , $m_{(V2X)_j}$ , and $X_{\sigma(V2X)_{j_{(dB)}}}$ are given in [15]. If these values are not available (since they could be captured from real-world by SDC during operation), theoretical propagation model could be used. However, talking about the capturing and sharing data, SDC can be capturing the received signal level and the distance at various points from the Tx and report to common database. These data will be used to formulate the empirical propagation model using the SDC decision making software with the method of least square learning algorithm given in the appendix [15], [41]. By this way, the system will have access to updated realistic environmental propagation model. Therefore, for demonstration purpose, this proposed study will be using theoretical and empirical models in [15], [39], [40]

Similarly, the delay on information communicated between the referenced car and target-Rx is obtained as follows: If a vehicle is moving at a constant speed, the phase change for nth shifted ray path is [42]

$$\Delta\theta_n(t) = \frac{2\pi|\overrightarrow{\Delta p}|}{\lambda}(\cos\theta_n) \quad (13)$$

putting $\lambda = c/f$, in (13), c is the speed of light (m/s) and f is frequency of operation (in Hz). Hence,

$$\Delta\theta_n(t) = \frac{2\pi|\overrightarrow{\Delta p}|}{c/f}(\cos\theta_n) \quad (14)$$

And putting (6) in (14),

$$\Delta\theta_n(t) = \frac{2\pi V}{c/f}(\cos\theta_n)\times t \quad (15)$$

This is a linear function of time *t* [42]; from $angle = 2\pi Ft$, *F,* frequency in Hertz, therefore, the ray of signal will experience a frequency shift, $f_s$ given as

$$f_s = \frac{V\times f}{c}(\cos\theta_n) \quad (16)$$

This ranges from $-f_s\ to\ f_s$ . At maximum shift, $\theta_n = 0$, hence,

$$f_s = \frac{V\times f}{c} \quad (17)$$

Likewise, the signal propagation delay $t_d$ in one direction is given as

$$t_d = \frac{|\vec{l_n}|}{c} \quad (18)$$

## 3.2 Reliable Model and SDC Decision Making Algorithm

### 3.2.1 Reliable Model

The efficiency and reliability of the communication link is modeled in relative to how strong is the signal received to the noise or degradation caused by the complex and dynamic SDC environments which is a function of the propagation model. The signal-to-noise and interference ratio (SNIR) depends on various factors such as environment type, frequency, transmission power, antenna gain/height, equipment, noise etc, [43], [44], [45].

Accordingly, the signal-to-noise and interference ratio (SNIR) is:

$$SNIR[dB] = 10\log_{10}\left(\frac{P_r}{P_0 + \sum_{j=1}^{m} I_j}\right) \quad (19)$$

where $P_r$ is the received signal strength (W), $P_0$ is the noise power (W), $I_j$ is the interference from node *j*, and $m$ is the number of neighbors that contribute to the interference.

For practical V2X communication model to be used in implementing 5G NR C-V2X (PC5) standard, PC5 (direct communication mode) uses SC-FMDA (Single-carrier frequency-division multiple access) as modulation and coding scheme to reduce co-channel or adjacent interference.

Or when low power wide area network protocols are used in V2X communication employs O-QPSK (Offset quadrature phase shift keying) modulation schemes with direct sequence spread spectrum (DSSS). The intended receiver of DSSS signal can recover a weak signal as result of channel noise and interference with the aid of processing and coding gain used on the device. The transmitted signal has low probability of being intercepted [43], [44]. Therefore, co-channel interference can be neglected, and adjacent channel interference can be regarded as random and modeled into the noise power.

According to [43], [44], [45] the signal-to-noise ratio (SNR) per distance then becomes:

$$SNR(d)_{[dB]} = P_t - PL(d) - P_N \quad (20)$$

where $P_t$ is the transmit power (in $dBm$), $PL(d)$ is the propagation path loss model in $(dB)$, $P_N$ is the noise floor in $(dBm)$.

Similarly,

$$P_{N\ [dBm]} = 10\log_{10}(KTB_N) + F_{dB} \quad (21)$$

where $F_{dB}$ is the noise figure, $B_N$ is the noise or propagation bandwidth in (Hz), $KT = 4.1\times 10^{-18} mW/Hz$, with Boltzmann's constant, $K$ at room temperature, $T$ in Kelvin [45].

If (12) and (21) are substituted into (20), it becomes:

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$$SNR_{(V2X)_j}(d)_{[dB]} = P_{(V2X)_j t} - P_{l(V2X)_j}(d_o)(dB) - 10m_{(V2X)_j}\log_{10}\left(\frac{\vec{V}\times\Delta t}{\cos\left(\tan^{-1}\left(\frac{|\vec{l_0}|}{|\vec{\Delta p}|}\right)\right)}\right) - X_{\sigma(V2X)_{j(dB)}} - 10\log_{10}(KTB_N)_{(V2X)_j} - F_{(V2X)_{j\,dB}} \qquad (22)$$

Where $(V2X)_j$ is respective V2X propagation model. Similarly, the respective V2X energy per bit to noise spectral density, $\frac{E_b}{N_{0\,linear}}$ is related to $SNR$ in linear as [43], [45]:

$$\frac{E_b}{N_{0\,(V2X)_j linear}} = SNR_{(V2X)_j linear} \times \left(\frac{B}{R_b}\right)_{(V2X)_j} \qquad (23)$$

where $R_b$ is the data rate (in bits/s), $B$ is the bandwidth per channel in (Hz) for respective V2X propagation model. These variables and parameters are function of the transceiver hardware of the Tx and Rx and communication channel specifications.

Substituting (22) in (23), thus, $\frac{E_b}{N_{0\,linear}}$,

$$\frac{E_b}{N_{0\,(V2X)_j linear}} = \left(10^{0.1\times SNR_{(V2X)_j}(d)_{[dB]}}\right) \times \left(\frac{B}{R_b}\right)_{(V2X)_j} \qquad (24)$$

Or $\frac{E_b}{N_{0\,(V2X)_j dB}} = 10 \times \log_{10}\frac{E_b}{N_{0\,(V2X)_j linear}}$, according to [44], [46], it has been proved experimentally that $\frac{E_b}{N_0}$ must be greater than $-1.592dB$ or $0.693$ to have a reliable or efficient communication. That is, the transmitted information bits will be recovered successfully at the receiver. Therefore, reliable communication is possible at a distance where

$$\frac{E_b}{N_{0\,(V2X)_j dB}} > -1.592dB \qquad (25)$$

and the referenced car would be able to communicate efficiently with the target station at that distance. Finally, the spectral efficiency ($SPE$) in b/s/Hz is the information rate that can be transmitted given a channel parameter and capacity, [44], [45]:

$$SPE_{(V2X)_j} = \log_2\left(1 + SNR_{(V2X)_j linear}\right) \qquad (26)$$

$SPE_{(V2X)_j}$ is plotted against the $\frac{E_b}{N_{0\,(V2X)_j linear}}$ to show the information transmission curve and range for reliability based on capacity.

### 3.2.2 SDC Decision Making Algorithm

The algorithm where the efficient V2X model could be fused into the SDC decision making software is described here. As discussed in Section 3.1., assuming there is a shared or on-board database, the SDC decision making software will access the database to formulate or use update experimental propagation model and if not available, it selects the theoretical model (free space or Winner II model)–the default. SDC software determines the delay on the information to be transmitted using (18), if delay will not allow reliable decision to be made on time, software adjusts safely vehicle speed or locates routing hop, else, it proceeds with decision making and communicating to V2X. The proposed efficient V2X communication approach is incorporated into an existing SDC AI decision making software (central processor) as depicted in Fig. 3. The communication algorithm is given in Fig. 4.

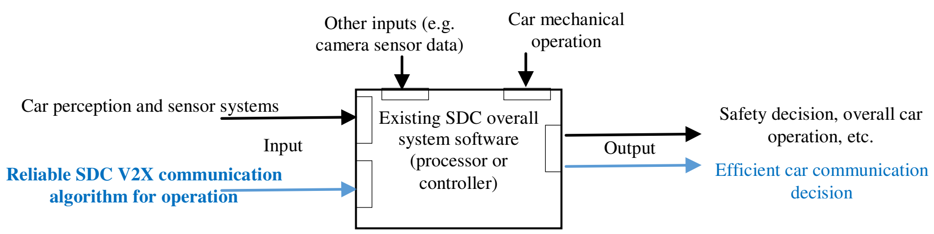


**Fig.3. Incorporating SDC V2X communication algorithm into SDC Central software & processor.**

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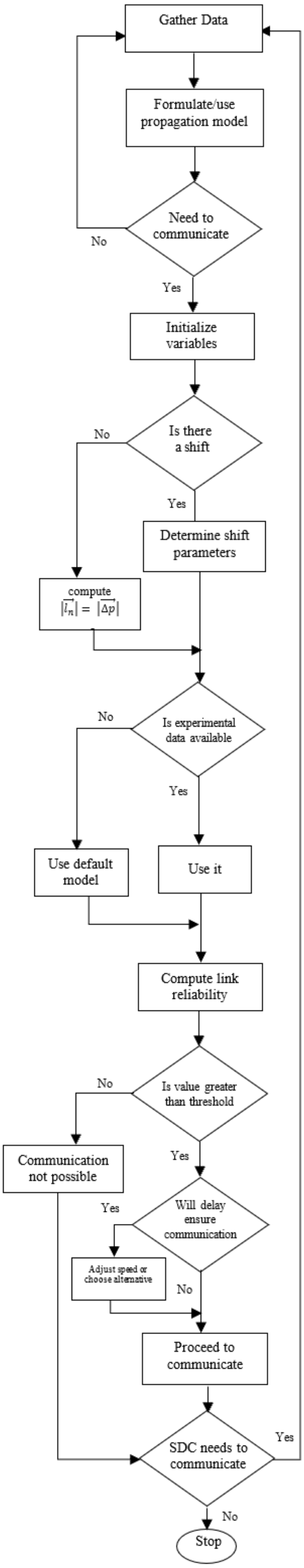


**Step 1:**
SDC software measures and gathers global communication and environmental data and store into car database or remote infrastructure database.

**Step 2:**
SDC software formulates or uses experimental signal propagation communication model using method of least square learning algorithm. Default theoretical model is already existing in the database or memory. Make models readily available for future use

**Step 3:**
SDC software determines if there is need to communicate with everything or anything in the environments and make communication decision. If yes, go to initialize variables from database or memory

**Step 4:**
SDC software initializes the respective transceiver hardware (Tx/Rx) parameters, link reliability threshold, $\frac{E_b}{N_{0_{dB}}} = -1.59dB$, $c$, speed (m/s) and time from the speedometer. And other parameters from the database. Part of this process is done from car ignition starts.

**Step 5:**
SDC software determines if there is a signal shift between a referenced SDC and target things or car to communicate to.

**Step 6:**
SDC software determines from database the infrastructure height (constant), that is $l_0$. It determines if the target station (Tx/Rx) not in the same direction and not in SLOS, then, there will be a shift, then, go to step 6, else go to step 7.

**Step 7:**
Based on the current new speed and change in time, using (3), software determines angle of shift, $\theta_n$ and change in position, $|\vec{\Delta p}|$ to a new position with respective to ray of signal shift from Tx/Rx. Thus, the software computes the length of shifted signal ray, $|\vec{l_n}|$ using (7).

**Step 8:**
Since software determines if there will be no shift and based on the current new speed and change in time, it computes length of signal ray as $|\vec{l_n}| = |\vec{\Delta p}|$.

**Step 9:**
Software iterates database, is up-to-date experimental propagation model available (that is (12), if yes apply this, else select default- (9).

**Step 10:**

From initialized parameters and using (23), the software computes the link reliability value, $\frac{E_b}{N_{0\,linear}}$

$$\frac{E_b}{N_{0\,(V2X)_j,linear}} = \left(10^{0.1\times SNR_{(V2X)_j}(d)[dB]}\right) \times \left(\frac{B}{R_b}\right)_{(V2X)_j}$$

**Step 11:**
SDC software determines if the link reliability value, $\frac{E_b}{N_{0\,(V2X)_j,dB}}$ is greater than threshold ($-1.592dB$), if yes, proceed with communication with target Tx/Rx, else software determines the closer Tx/Rx as routing node or hop to the target.

**Step 12:**
SDC software determines the delay on the information to be transmitted using (18), if delay will not allow decision to be made on time, software adjusts safely vehicle speed or locate routing hop, else, proceed with decision making and communicating to V2X.

**Step 13:**
If $\frac{E_b}{N_{0_{(V2X)_j,dB}}} > -1.592dB$ and $t_d$ is less than safety spec (driving time/distance) delay
SDC proceeds with communication to target or choose alternative

**Step 14:**
SDC software goes to step 2, repeats process when needed to communicate until vehicle stops

**Fig.4. SDC V2X Communication Algorithm.**

## 4. ANALYSIS AND RESULTS

### 4.1 Model Analysis and Results

This proposed approach is demonstrated and tested using the study in [15], [39], [40]. The result of the model is analyzed here. This proposed study assumes the following test scenarios and since the study is adopting the propagation loss model in [15] for demonstration purpose, therefore, this study uses its variables, parameters, and Tx/Rx specifications (Table 1). Thus, the representative propagation models for vehicular environments, (V2V) are $55.21 + 37.10\ \log_{10} d$ [15] and $43.79 + 28.07\ \log_{10} d$, [39], $d$ is the distance between Tx and Rx, $B_N$ is manufacturer specified device operation bandwidth (2.4GHz), $X_{\sigma(dB)} = 11.9dB$ , $R_b$ is the manufacturer specified data rate (250000 bits/s) for the device, and $B$ is the manufacturer specified bandwidth per channel (100 MHz or 150 MHz ) [45], [47]. Using the specifications in Table 1 and substituting the various variables into the equations in Section 3; and assuming various constant speeds; and for simplicity, constant time covered (per distance [time (s)]) to be 4 s, 25 s; the results of the proposed study are shown in Tables 2-4, and in Figs. 5 to 8. It can be seen in the tables and the figures that as the speed increases, the signal propagation model loss increases and consequently, the $\frac{E_b}{N_{0(V2X)_j}}$ reduces. This will impact how SDC V2X communication will operate. The tables also show the distance at which there could be a reliable communication of information between Tx and Rx for various SDC speeds. Also, the delay on the information to be transmitted between Tx and Rx increases. Likewise, Table 2 also shows the performance of the efficient communication algorithm modeled into the SDC decision making software. The software can make decision in less than $1ms$ for $25\ s$ simulation period performed on MATLAB 2019b platform [48]. The algorithm (or the software) needs to be efficient and fast in processing and executing enough to augment for the delay that may come as result of increase in speed and reduction in $\frac{E_b}{N_{0(V2X)_j}}$ . At a particular speed, and a referenced car is attempting to directly communicate with another target station, the software proceeds with the transfer of information when it determines that the $\frac{E_b}{N_{0(V2X)_j dB}} > -1.592dB.$ Otherwise, it seeks the alternative. That is, the software safely adjusts the vehicle speed or choose another station with a better $\frac{E_b}{N_{0(V2X)_j}}$ as relay station to the target station

**Table 1: Parameter and Variable Specifications Based on Hardware Transceiver used in** [15]**,** [39] , [40]

| Parameters | Values (V2V) [26], [39] | Values (V2I) [40] |
|---|---|---|
| $P_t$ | $18dBm$ [26], $3dBm$ [39] | $35.7dBm$ |
| $Propagation\ model$ | $55.21 + 37.10\ \log_{10} d$ [26] | $39.26 + 20.70\ \log_{10} d$ |
| $Propagation\ model$ | $43.79 + 28.07\ \log_{10} d$ [39] | - |
| $X_{\sigma(dB)}$ | $11.9dB$ [26], $12dB$ [39] | $4.89dB$ |
| $KT$ | $4.1 \times 10^{-18} mW/Hz$ | $4.1 \times 10^{-18} mW/Hz$ |
| $F_{dB}$ | $0dB$ | $4.96dB$ |
| $B_N$ | $2.4GHz$ | $3.5GHz$ |
| $B$ | $100/150MHz$ | $150/300MHz$ |
| $R_b$ | $250kbits/second$ | $250kbits/second$ |
| $gt$ | $1.5dB$ | $10dB$ |
| $gr$ | $1.5dB$ | $11dB$ |

**Table 2: The V2X Communication Link Analysis Results Assuming 4s Time (V2X-V2V)**

| Speed (mph) | Propagation loss (dB) | Tx Delay (RTT) (µs) | Doppler shift (Hz) | Distance (m) at the loss | SDC software execution time (ms) for t=1 to 25s | $Eb/No$ (dB) | SDC Decision $Eb/No > -1.59$ |
|---|---|---|---|---|---|---|---|
| 10 | 113.63 | 0.1196 | 35.76 | 17.94 | 0.774 | 12.052 | *proceed* |
| 20 | 124.76 | 0.2386 | 71.53 | 35.79 | 0.780 | 0.9230 | *proceed* |
| 30 | 131.28 | 0.3578 | 107.29 | 53.66 | 0.801 | -.5.603 | *alternative* |
| 40 | 135.91 | 0.4770 | 143.05 | 71.54 | 0.880 | -10.236 | *alternative* |
| 50 | 139.51 | 0.5962 | 178.82 | 89.42 | 0.886 | -13.830 | *alternative* |
| 60 | 142.45 | 0.7154 | 214.58 | 107.30 | 0.907 | -16.767 | *alternative* |
| 70 | 144.93 | 0.8346 | 250.34 | 125.18 | 0.914 | -19.250 | *alternative* |

**Table 3: The V2X Communication Link Analysis Results Assuming 25s Time (V2X-V2V)**

| Speed (mph) | Tx Delay (RTT) (µs) | Doppler shift (Hz) | Distance (m) | $Eb/No$ (dB) | SDC Decision $Eb/No > -1.59$ |
|---|---|---|---|---|---|
| 10 | 0.0313 | 35.76 | 4.69 | 36.036 | *proceed* |
| 20 | 0.1018 | 71.53 | 15.27 | 21.660 | *proceed* |
| 30 | 0.2148 | 107.29 | 32.22 | 12.556 | *proceed* |
| 40 | 0.3339 | 143.05 | 50.09 | 7.1765 | *proceed* |
| 50 | 0.4471 | 178.82 | 67.07 | 3.6174 | *proceed* |
| 60 | 0.5723 | 214.58 | 85.84 | 0.6091 | *proceed* |
| 70 | 0.6885 | 250.34 | 125.18 | -1.6447 | *alternative* |

**Table 4: The V2X Communication Link Analysis Results Assuming 25s Tim2 (V2X-V2I)**

| Speed (mph) | Tx Delay (RTT) (µs) | Doppler shift (Hz) | Distance (m) | $Eb/No$ (dB) | SDC Decision $Eb/No > -1.59$ |
|---|---|---|---|---|---|
| 10 | 0.7451 | 52.15 | 111.76 | 49.87 | *proceed* |
| 20 | 1.4902 | 104.31 | 223.52 | 43.64 | *proceed* |
| 30 | 2.2352 | 156.46 | 335.28 | 39.99 | *proceed* |
| 40 | 2.9803 | 208.62 | 447.04 | 37.40 | *proceed* |
| 50 | 3.7253 | 260.77 | 558.80 | 35.40 | *proceed* |
| 60 | 4.4704 | 312.93 | 670.56 | 33.76 | *proceed* |
| 70 | 5.2155 | 360.08 | 782.32 | 32.37 | *proceed* |

Furthermore, Tables 2-4 shows the Doppler frequency shifts that determine how severe are the signal rays shifted or impacted due to SDC speed and signal operating frequency which in turn affects the SNR. Similarly, in the tables, assuming a communication distance time of 25s per speed, for V2V communication of V2X in highly signal impacted V2X environments, as shown in Table 2, the propagation signal is lost at this distance at all vehicular speeds. However, V2X-V2V communication is possible between the Tx station and Rx station for a communication distance time of 4s at 20 mph and below with $Eb/No\,(0.9230\,dB)$ greater than $-1.592\,d$ . Similarly, in a less complex V2X environment, (as shown in [39]) and Table 3), V2X-V2V communication is possible at communication distance time of 25s for vehicle speed less than 60 mph (with $Eb/No =$ $0.6091\,dB$).

Whereas, for V2I communication of V2X where propagation is like free space, there is no obstruction to signal propagation due to heterogeneous V2X-V2I environments. In this condition, V2X communication is possible at 70 mph and covering approximately 800 m distance.

Therefore, in complex SDC environments, V2X communication may be impaired if assuming V2I propagation modeling for V2V or V2P in V2X communications. The V2I propagation model will overpredict for V2V or V2P in V2X communications. From the result in Table 4, apart from being a signal propagation in free space, high transmission power (35.7 dBm) might have also contributed to having good $Eb/No$ and the long range achieved. However, as it is observed in Fig. 9, the free space or theoretical model has the same transmission power (18 dBm) with the proposed and experimental V2V models and the free space V2I model still over performs.

Consequently, it is important that if direct V2X communication is required, the proposed algorithm will select an appropriate V2X propagation model (V2X communications-V2V, V2I, V2P, V2H, V2N, V2C, V2E, and V2T).

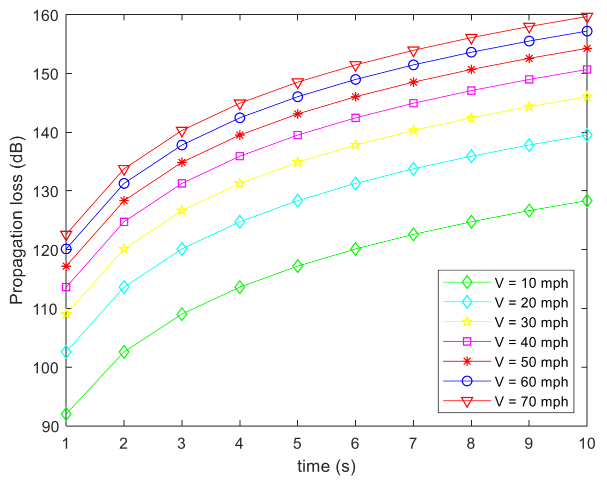


**Fig. 5. Propagation loss at various speeds (V2X-V2V).**

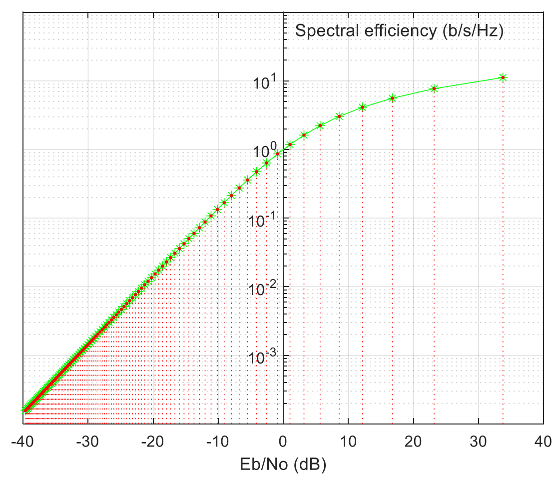


**Fig. 7. Plot for spectral efficiency vs $Eb/No$ (V2X-V2V)**

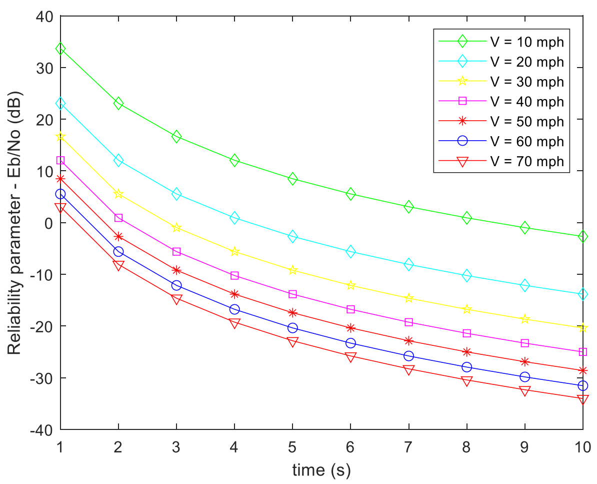


**Fig. 6. Reliability parameters – $Eb/No$ at various speeds (V2X-V2V).**

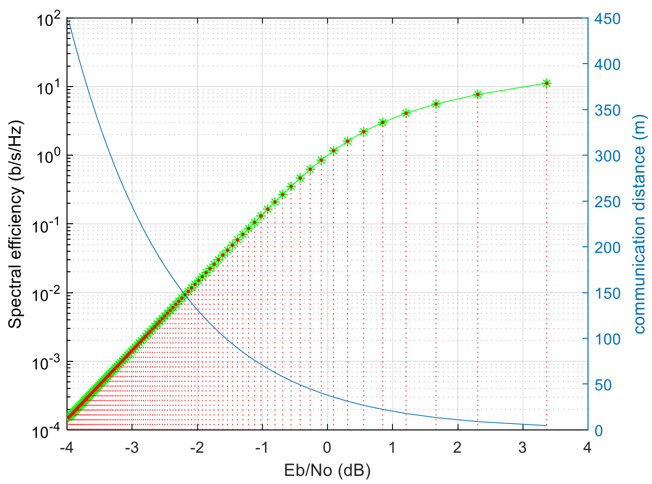


**Fig. 8. Reliability parameters and at respective communication distance and time 1 to 100 s (V2X-V2V)**

### 4.2 Validation of the Proposed Models

To further validate the proposed approach, the proposed algorithm result is compared with the theoretical model, existing study, and experimental results. This study extrapolates the reliability factors using theory and experiment in [15] by obtaining respective $Eb/No$ values. These values are scaled to 100 percent (reliability factor = respective each $Eb/No$ divided by the highest $Eb/No$ for each model) at various speeds as shown in Fig. 9. Some statistics such as mean absolute percentage error, (MAPE) and P-values are used to test the significance of the comparison [15], [41], [49], [50]. The $MAPE(4)$ expresses accuracy as a percentage of error [49].

$$MAPE = \frac{1}{n}\sum_{x=1}^{n}\left|\frac{Pm_x - Tm_x}{Pm_x}\right| \times 100\% \qquad (27)$$

where $Pm_x$ is the $x^{th}$ proposed model value, $Tm_x$ is $x^{th}$ theoretical or experiment value, and $n$ is number of samples.

According to [15], [49], [50], it has been shown by various examples of comparing forecast data with original data that for a better prediction or accuracy of forecasting, it is accurate to have $MAPE$ that is less than or equal to 10 %. The values are obtained by "rule of thumb" as approximation bound to test the significant of prediction [15].

Also, MSE is used to check the accuracy of the communication algorithm.

$$MSE = \sum_{x=1}^{n}\frac{(Pm_x - Tm_x)^2}{n-1} \qquad (28)$$

The result of the comparison is shown in Tables 4 and 6. The $MAPE$ of theoretical or free space model results compared with proposed reliable algorithm is high– 30 % which is more than 10 %. Also, the P-Values is 0.000 which is less than the chosen value alpha = 0.05 at 95 % confidence interval in the statistical comparison. Therefore, the theory is less efficient compared to the experimental model and proposed approach. Also, the $MAPE$ of the proposed reliable algorithm compared with experimental results is 7 % which is less than 10%. Likewise, the P-value [41] is 0.947 which is more than the chosen alpha = 0.05. It also has low MSE. This confirms the hypothesis, that the proposed model result is similar to real life deployment (experiment). This means that the communication decision from the SDC decision making software will be dependable. From Figs. 9 and 10, employing all the three models, the communication software will be approximately 80 % efficient (reliability factor) at a speed less than 40 mph and 100 % at a speed less than 20 mph. Also, the proposed approach software is 60 % efficient at a speed up to 70 mph in a highly signal impacted SDC complex environment case. Similarly, the proposed approach is 99% efficient at an average speed of 70 mph in a less signal impacted or free space SDC environment case (e.g. Table 4) at $Eb/No$ greater than $-1.592\ dB$ . It is therefore recommended to use measured data for the propagation model in the proposed approach.

It is also recommended in this study that the Tx/Rx (infrastructure) should be high and greater than 1.434 m–height of a sedan car for better distance of communication covered and effective communication.

Furthermore, the comparison with existing model shows that the proposed model has shorter TX delay. The proposed V2X communication model is compared with existing V2V communication result in [6] as shown in Tables 5 and 6. It can be seen from the table that at a lower speed (30mph), reliable communication can take place with delay of approximately 2µs round trip time (RTT) compared to [6] with delay of approximately 200µs.

In addition, a demonstration plot for SDC V2X communication link using the open-source MATLAB automated driving toolbox [48], is shown in Fig. 10. From the figure, a referenced car (RC)- (blue) moving with a particular speed could communicate with two other cars- gold, and brown moving at difference speeds and with other communication enabled entities in the vehicular environments. RC SDC V2X software identifies the two cars and could communicate with them at that distance and speed based on the SDC V2X communication algorithm decision.

**Table 5: Statistics for Reliability Comparison between Theory and Proposed SDC V2X Communication Model**

| Models | Proposed Model | | |
|---|---|---|---|
| | MSE | MAPE (%) | P-value |
| *Theory* | 0.0974 | 30.09 | 0.000 |
| *Experiment* | 0.0059 | 7.23 | 0.947 |

**Table 6: Comparison between Existing Model and Proposed SDC V2X Communication Model**

| Parameters | Existing (V2I/V2V) [6] | Proposed SDC V2X |
|---|---|---|
| *Speed (mph)* | 37 | 37 |
| *Tx delay (µs)* | ~288 | ~2 |

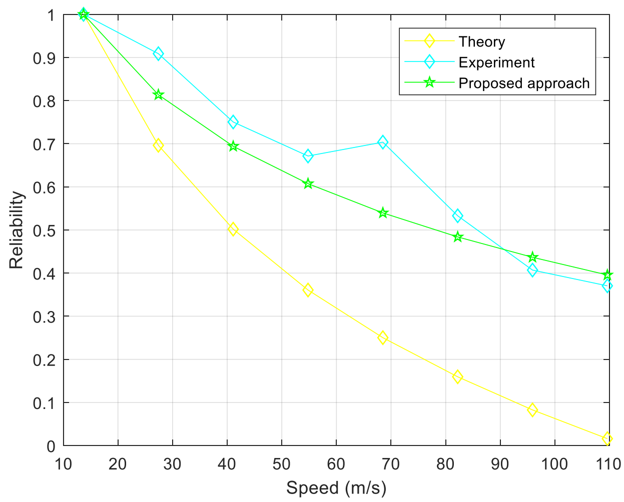


**Fig. 9. Plot for the comparison between theoretical and proposed communication model for SDC deployment in vehicle environments (V2X).**

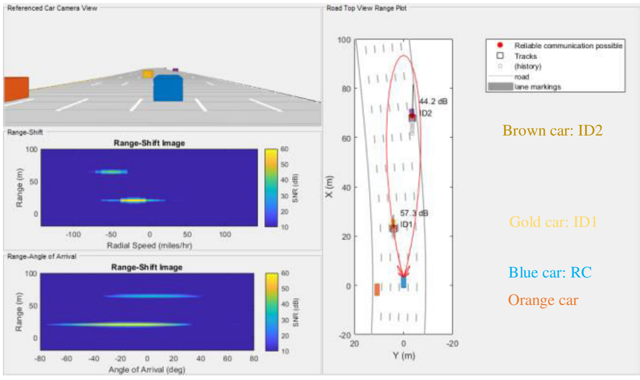


**Fig. 10. Plot for SDC communication simulation on open-source MATLAB 2019b (V2X-V2V).**

## 5. CONCLUSION

This proposed study presents an efficient SDC V2X communication link algorithm modeled into SDC decision making software that will enhance the communication operation of SDC and other benefits of implementing SDC technology. The results show that the proposed communication algorithm in SDC decision making is efficient. The proposed approach is compared with theoretical model, existing study, and experimental study. The results show that the propose V2X communication model outperforms the V2V communication and theoretical models in literature and in similarity with experimental study. Hence, the proposed approach can make the operation of SDC more efficient.

Future study will include the use of RADAR and LIDAR sensor signal to determine $|\vec{l_n}|$ in addition to regular radio wave band for communication and at the same time for sensing purposes. By this approach, it may reduce computational effort of central processor and make the processor even faster. Also, it may save resources (hardware and frequency band) and reducing interference and signal collisions from multiples sources. The approach can be extended to as many new SDC V2X communication parameters that will be identified and defined. Future study will also be the analysis on SDC V2X communication security.

### APPENDIX A

***Method of least square learning algorithm:***

Method of least square is typically used to estimate the regression coefficients in a multiple or linear regression model like first order log-distance propagation model. The least square function is given as (2) [41], [51].

Given an input label x, and output label y as large training data, find a classifier Y that can predict new value of y given a new input x. That is,

$$y = Y(x) = \beta_0 + \beta_1 x \qquad (A-1)$$

Where $\beta_0$ and $\beta_1$ are the parameters of the model and are called **regression coefficients**

The least squares method is a systematic approach to fit a linear model to the response/target variable ***y*** by minimizing error between the true and estimated value of ***y***. Method of least square is typically used to estimate the regression coefficients in a multiple or linear regression model. The method of least squares chooses the value of $\beta$ so that the sum of the squares of error ($\varepsilon$) is minimized. The least square function is

$$\boldsymbol{L} = \sum_{i=1}^{n} \varepsilon_i^2 = \sum_{i=1}^{n}\left(y_i - \beta_0 - \sum_{j=1}^{k}\beta_j x_{ij}\right)^2 \qquad (A-2)$$

Therefore, find the optimal point, that is, find $\hat{\beta}$ while minimizing ***L***

$$\hat{\beta} = argmin_{\ b\in R}\ \boldsymbol{L}(\beta_0, \beta_1) \qquad (A-3)$$

At minimum, L, the classifier becomes

$$Y(x) = \beta_0 + \beta_1 x \qquad (A-4)$$

The objective is to choose β so as to minimize ***L(β)***. To do so, let's use a search algorithm that starts with some "initial guess" for β, and that repeatedly changes $\beta$ to make ***L(β)*** smaller, until hopefully it will converge to a value of β that minimizes ***L(β)***. Specifically, let's consider the gradient descent algorithm, which starts with some initial β, and repeatedly performs the update:

$$\beta = \beta_i - \alpha \frac{\partial}{\partial \beta_i}\boldsymbol{L}(\beta) \qquad (A-5)$$

Here, α is called the learning rate. This is a very natural algorithm that repeatedly takes a step in the direction of steepest decrease of ***L***. we'll have the following minimization algorithm based on gradient descent: Repeat until converge.

It is easier to solve this normal equation if it is expressed in matrix form given as:

$$y = x\beta + \epsilon$$

$$y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ \vdots \\ y_n \end{bmatrix},\ x = \begin{bmatrix} 1 & x_{11} & x_{12} & .. & x_{1k} \\ 1 & x_{21} & x_{22} & .. & x_{2k} \\ \vdots & \vdots & \vdots & .. & \vdots \\ \vdots & \vdots & \vdots & .. & \vdots \\ 1 & x_{n1} & x_{n2} & .. & x_{nk} \end{bmatrix},\ \beta = \begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \vdots \\ \beta_k \end{bmatrix} \text{ and } \epsilon = \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \vdots \\ \vdots \\ \epsilon_n \end{bmatrix} \qquad A-6$$

where $y$ is the output, $x$ is the input sample, $n$ and $k$ are the number of observations, and $\epsilon$ is the error.

The task of finding solutions to equation (2) becomes an optimization problem, that is, find the vector of least square estimate that minimizes ***L*** in equation (2), the least square estimate of $\beta$ is given as:

In matrix notation,

$$\hat{\beta} = (x'x)^{-1}x'y \qquad (A-7)$$

Hence, the classifier becomes

$$Y(x) = \beta_0 + \beta_1 x$$

Therefore, for given input distance, $d$ that is $x$, which is the Log of ($d$), the predicted path loss model ($dB$ ) is:

$$\widehat{P_{lp}} = \beta_1 x + \beta_0 \qquad (A-8)$$

$$\widehat{P_{lp}} = 10m\log_{10}\left(\frac{d}{d_o}\right) + P_l(d_o)_{(dB)} \qquad (A-9)$$

where $\beta_1 = 10m$, $x = \log_{10}\left(\frac{d}{d_o}\right)$ and $\beta_0 = P_l(d_o)_{(dB)}$

### APPENDIX B

Similarly, to convert miles per hour to meter per second:

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$$V(m/s) = \frac{V(mph) \times 1609.34}{3600} \qquad (B-1)$$

A transmitted signal ray, $v(t)$ is represented by

$$v(t) = A \sin 2\pi F t \qquad (B-2)$$

where $A$ is the amplitude of the signal (e.g $A = 1$) and is $F$, frequency in *Hertz,* and time, t in seconds.

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